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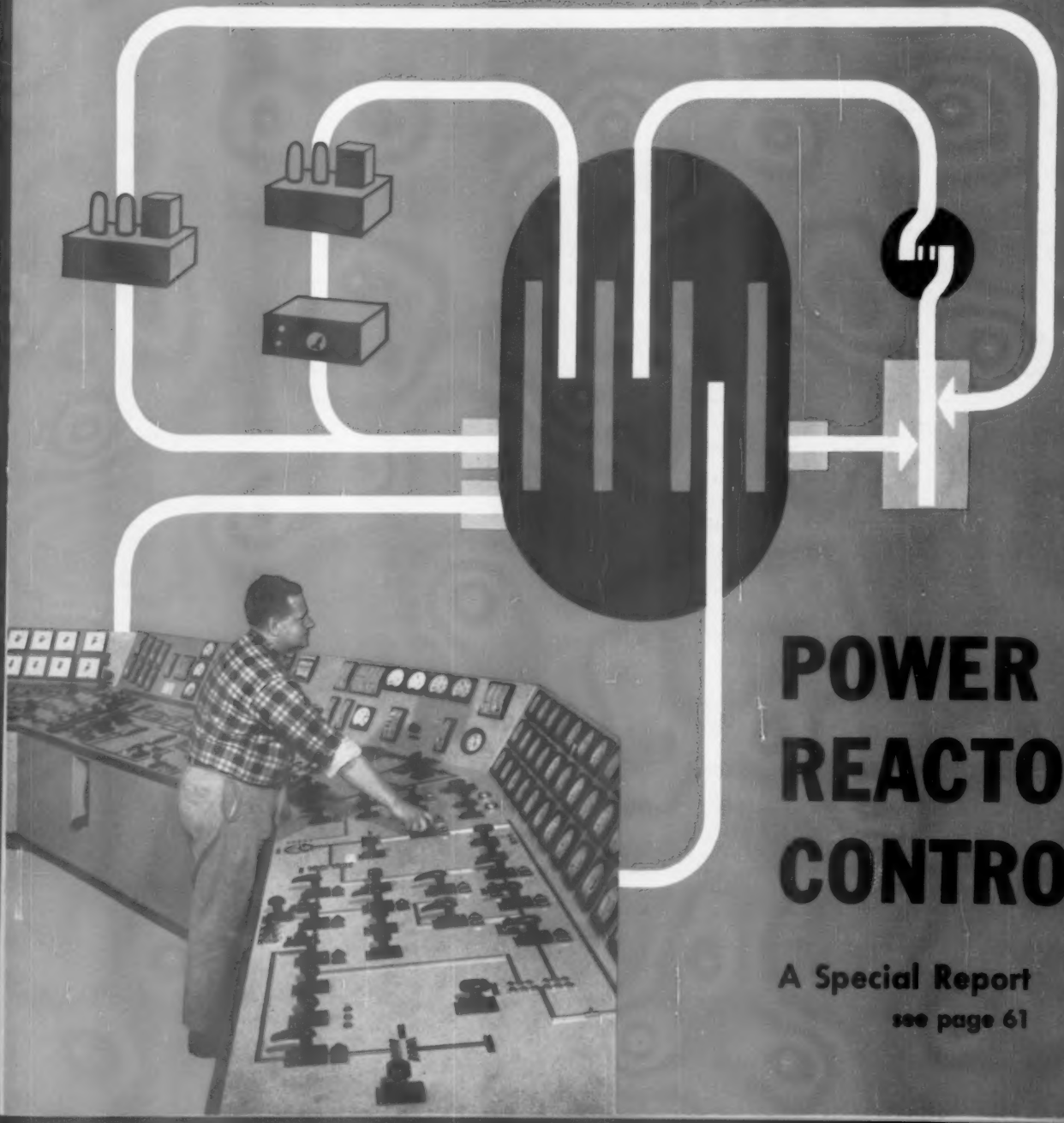
NUCLEONICS

ATOMIC POWER • NUCLEAR ENGINEERING • APPLIED RADIATION



POWER REACTOR CONTROL

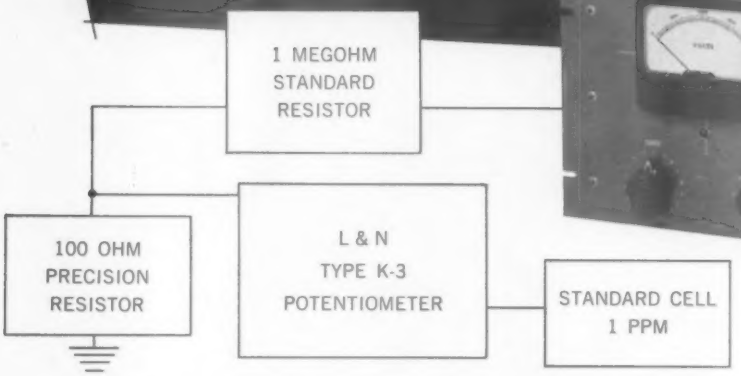
A Special Report

see page 61

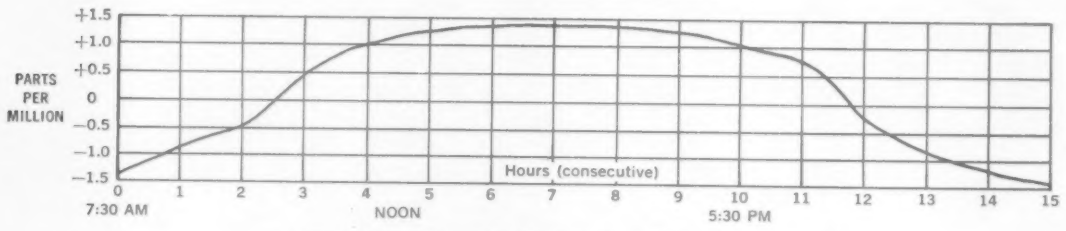
Hammer

POWER SUPPLY SURPASSES EXPECTATIONS

The Ultimate in Stability Proved In Precision X-Ray Spectroscopy Laboratory Test



MODEL N-401 REGULATED HIGH VOLTAGE POWER SUPPLY



Graph Shows Long Term Stability To Be Better Than ±1.5 Parts Per Million

The Johns Hopkins University Precision X-Ray Laboratory recently tested the stability of a Model N-401 Regulated High Voltage Power Supply *for a period of 15 hours. The voltage was constant within ±1.5 part per million* as shown by the graph. The power supply was in use approximately 2000 hours and tested in an ambient temperature of 24.00° ±0.05° centigrade.

- **The Model N-401 is a new concept in regulated power supply design — it provides up to 5 MA of current and negative or positive DC voltage — continuously variable from 500 to 1800 volts.**
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About NUCLEONICS

Our Undersea Editor

Being able to combine avocational enthusiasms with vocational duties not only produces a happy man, but brings bonus to his outfit. This is the case with NUCLEONICS' *peripatetic News Editor Kenton, who, calling himself a "frustrated naval architect," keeps up-to-date on the world's ocean liners, and studies piloting and navigation as hobbies, while seeing that we stay abreast of maritime developments with prize-winning stories like last July's piece on the nuclear navy. Here is his report on a one-day cruise aboard the nuclear submarine* Seawolf *last month.*

Boarded *Seawolf* 0730 at Electric Boat dock. Sunny day, mild breeze. Other two-thirds of nuclear fleet, *Nautilus* and *Skate*, moored nearby, having new sonar gear installed. Departure signaled by blast of deep-throated steam whistle more appropriate to *Queen Elizabeth* than to wispy silhouette of a submarine. "0801—underway on main turbines" read entry in ship's log. Phrase less dramatic than *Nautilus'* historic first signal "underway on nuclear power," but very idea of turbines on a submarine tells story.

ROVING editor finds reader at bottom of sea

Proceeded swiftly down gray Thames river for exercises with conventional sub *Croaker* between Fisher's I. and Montauk Point. When time for first dive neared, Navy officers, with rare tact, suggested to press party cluttering up foredeck: "Coffee is now being served in the wardroom." Going down hatch from ship's forbidding battleship-gray deck into unexpectedly airy, pleasant brightly-lit wardroom much like Alice in Wonderland following rabbit down hole, finding living room at bottom. Here, too, wonderland at bottom. Or M. Aronnax on Jules Verne's *Nautilus*.

Happy discovery: long row of recent NUCLEONICS issues only periodical on shelves of ship's technical bookcase in turbogenerator compartment (*see photo*).

Most impressive among many impressive things noted: palatial habitability, smoothness of movement, reliability of power plant, flaming enthusiasm and confidence of officers and men in sodium-cooled reactor systems.

Habitability—elimination of main fuel-oil tanks makes *Seawolf* almost twice as roomy as conventional sub of similar length (although she does carry oil for emergency diesels with 20,000-mi range). This permits not only world's only undersea electric organ, 100-disk jukebox, wide-screen movie, TV set; traditional submarine compactness moderated by general spaciousness and roominess most unexpected in submersible. Allowance made for functional nature of *Seawolf* imposed by her duties, her interior compares to that of a World War II sub as *Ile de France* to a tramp freighter. Liveability a keynote of décor: soft fluorescent lighting, pastel-toned compartments ("to avoid getting the bulkhead stirs," said Navy man), airconditioning throughout, pale-green plastic mattress covers in men's bunks. Reenlistment rate high.

Smoothness—ship moves in complete silence. No vibration. Slight feeling of ship banking felt in soles of feet on 180° turns. Otherwise can't tell if surfaced or submerged, moving or moored.

Reliability—Since early troubles with superheater, *Seawolf* has logged over 38,000 mi on nuclear power. No hitches, no leaks, no adjustments. Reactor compartment has not been entered in 16 months. "No other reactor in world can say this," says soft-spoken Skipper Laning. *Seawolf* holds record for longest time underwater, 16 days. Finally surfaced only because "we ran out of sea."

Control Special

The 32-page special report on power-reactor control that is the main feature of this issue pretty much speaks for itself. So with a vote of thanks to the authors who contributed to it and kudos to Associate Editor Hoby Ellis who carried the main responsibility for the report we urge you to turn to p. 61.

—The Editors

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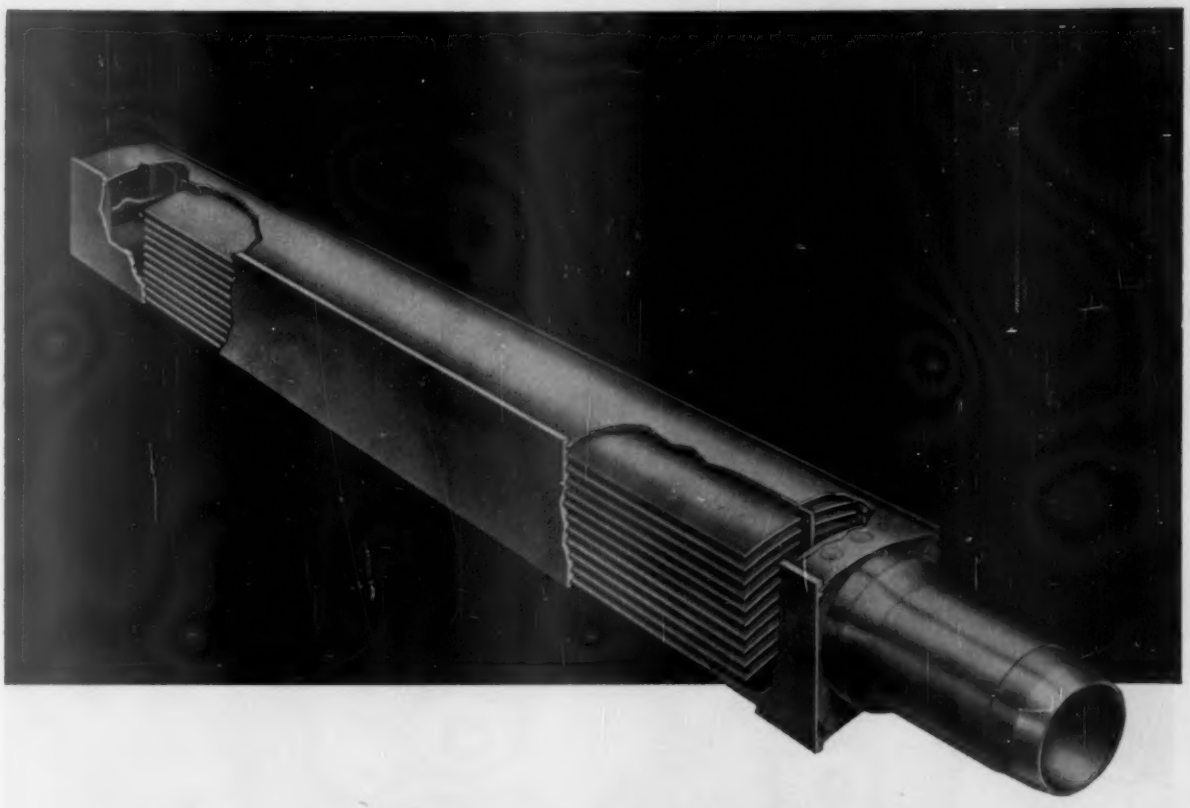

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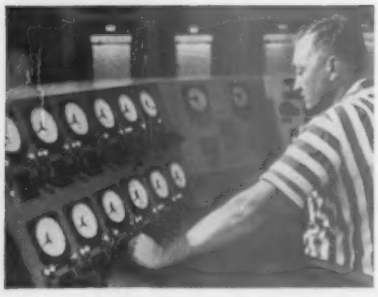
Under L&N controls, the ETR puts reactor components on trial

Written by R. N. Brey, in charge, Nuclear Systems Group, for this advertisement.



● The Engineering Test Reactor, a 175,000-kw nuclear reactor which went critical in September, is now being used for the testing of reactor components. The ETR contains the most advanced facilities yet devised for environmental studies of various fuels and other reactor materials under varying nuclear reactor pressures, temperatures, and amounts of radioactivity. Results of the tests are helping to determine the most efficient and economical reactor designs for the power systems of tomorrow.

Versatile controls required

The design of the ETR required a versatile control system that would do its job dependably under many conditions. Instruments were needed to provide information on a very large number of parameters, quickly and accurately. Controls for the ETR were planned by Leeds & Northrup as a single, coordinated system that would assure maximum precision and flexibility.

A six-channel system

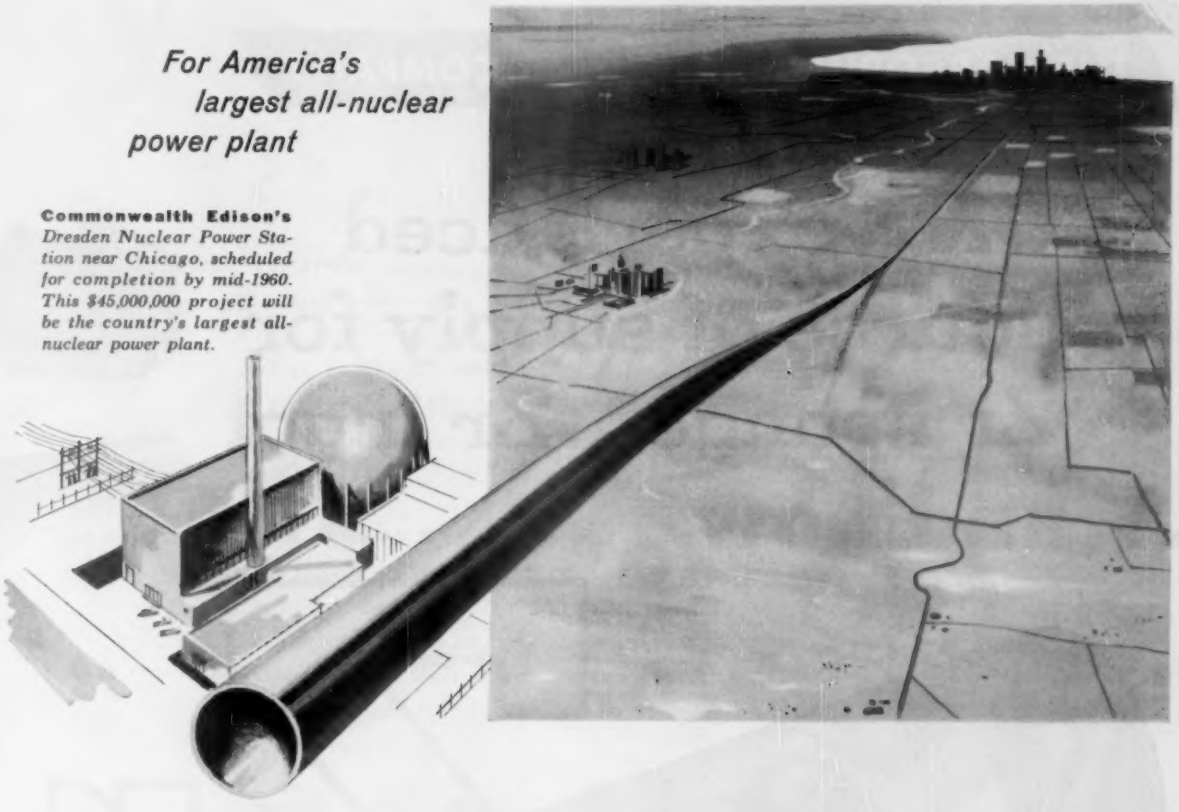
The reactor is controlled through six different channels. One, a pulse-counting channel, measures and controls power rise from the low level at start-up. As the power passes to higher levels a "log N-period" channel measures the rate of rise, and a servo channel maintains the reaction at preset operational levels through a feedback loop. A process-monitor channel controls water flow, temperatures, pressures and other sys-

Continued on page 97

LEEDS Instruments NORTHRUP Automatic Controls • Furnaces

For America's largest all-nuclear power plant

Commonwealth Edison's *Dresden Nuclear Power Station near Chicago, scheduled for completion by mid-1960. This $45,000,000 project will be the country's largest all-nuclear power plant.*



44 MILES OF ZIRCONIUM TUBING

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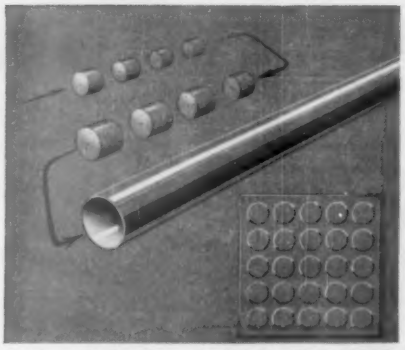

To form fuel rods, *cylindrical pellets of UO_2 are inserted in Zircaloy tubing. Tubes are sealed and welded, then assembled into "bundles" to form the rod-type element (inset).*

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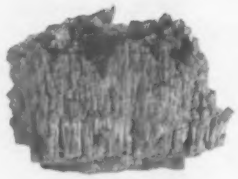

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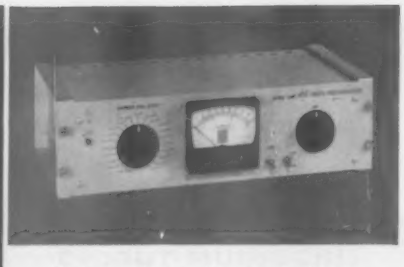

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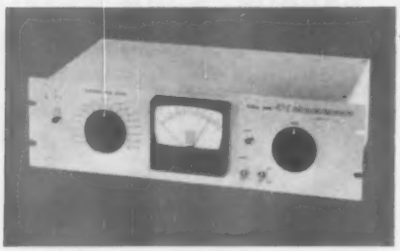

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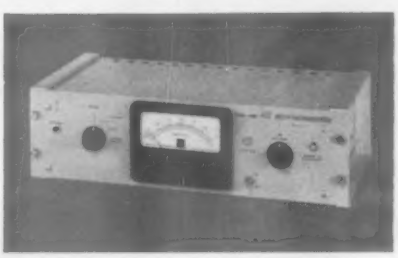

logarithmic models

The 412 Log n Amplifer has a large single scale, measuring 10^{-13} to 10^{-7} amp. with no range switching. Other features include zero drift within 0.05 decade in 24 hours, fast response and low output noise. (Model 413 with 10^{-11} to 10^{-5} ampere range also available.)

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*** Model 420**

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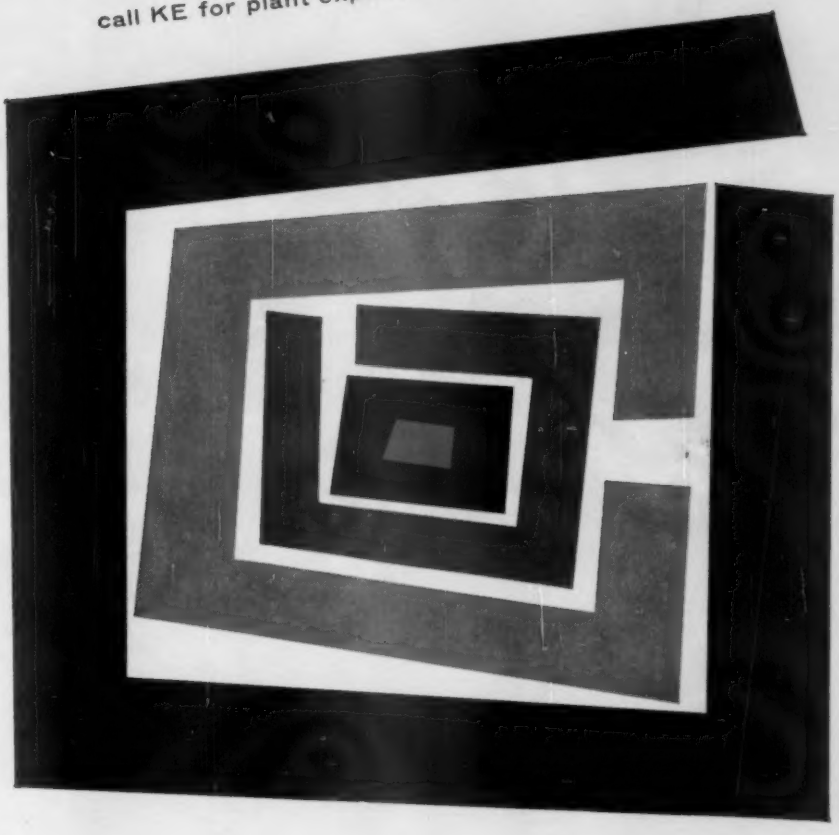

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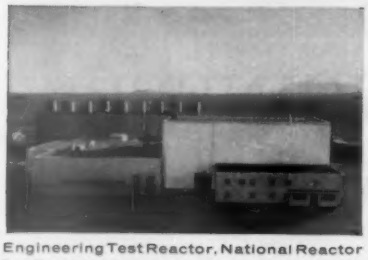

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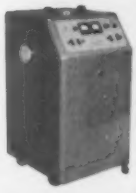

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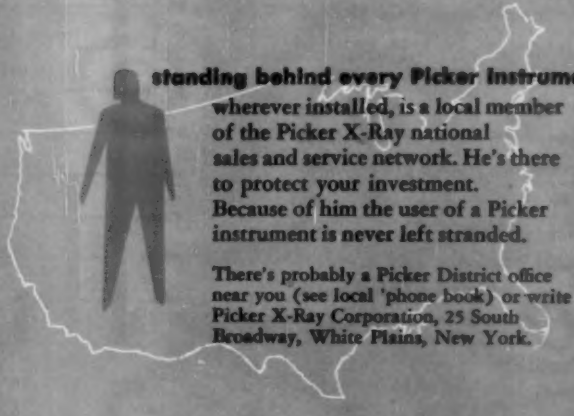

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Costs down sharply... large quantities available

a report by LINDSAY

Today you can buy at $50 per pound Samarium Oxide of 99% purity which in 1955 cost $1825—a price reduction of 97%, almost unprecedented in the chemical industry.

All high purity rare earths are priced substantially below the 1955 levels. Price ranges for four oxides, over a three-year period, are shown in the graphs.

During 1954, there was a rapidly developing industrial interest in high purity rare earths which were available then only in small, laboratory-production quantities and at very high prices.

In 1955, Lindsay pioneered the first commercially installed ion exchange pilot plant with 40 six-inch columns for the production of rare earth oxides in purities up to 99.99%. As these materials became available, the response from industry demonstrated that much larger production facilities were urgently needed.

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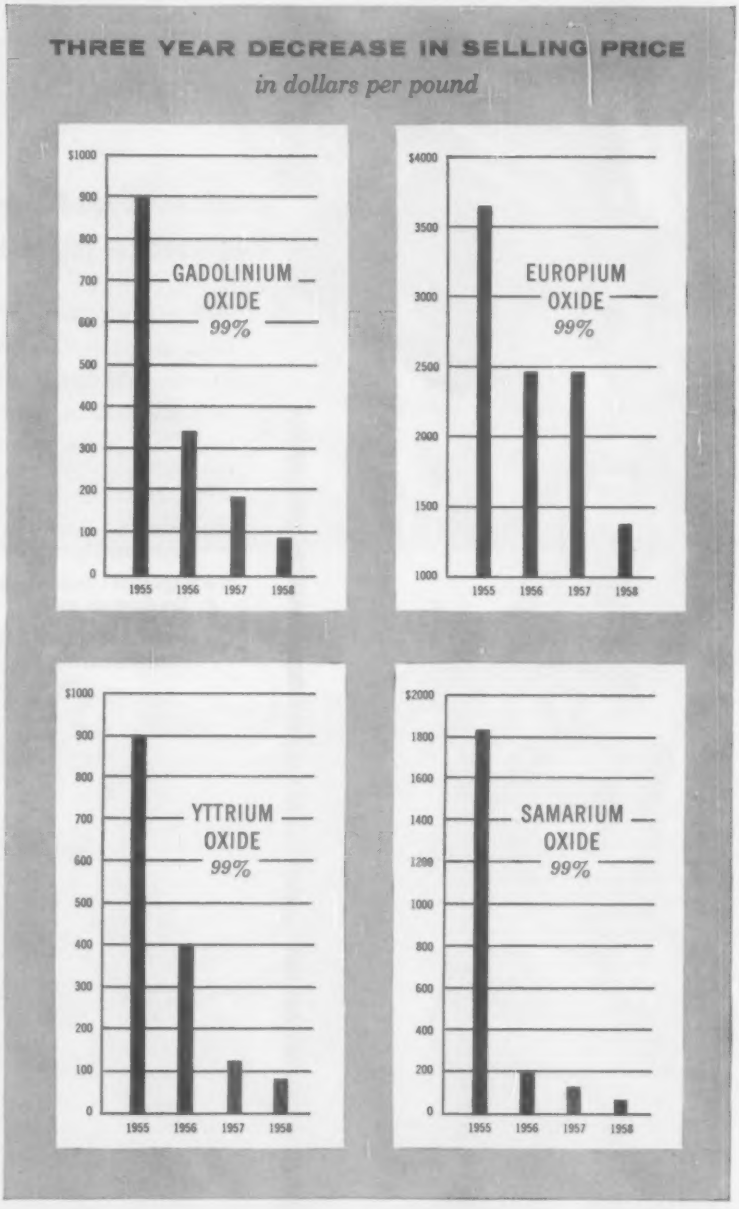
We will be happy to supply technical data and information about availabilities, prices and industrial applications.



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The Zirconium Age has arrived! Columbia-National's new sponge plant now offers you a ready source of reactor and commercial grade zirconium.

Uniform high quality zirconium is assured by converting zircon sand to sponge at one location under the responsibility of one management. The unique "Nitrophos" extraction process separates and purifies zirconium and hafnium in this plant.

Reactor-grade and hafnium-containing commercial-grade zirconium sponge are available for government and industrial requirements. Leading metal converters and fabricators are now supplying zirconium mill and finished products.

There is new opportunity in the Zirconium Age. You are urged to investigate its use in atomic reactors and in process equipment where corrosion conditions are severe. Columbia-National is ready to help with melting, fabrication and application assistance. Write for technical bulletin, specifying your interest.

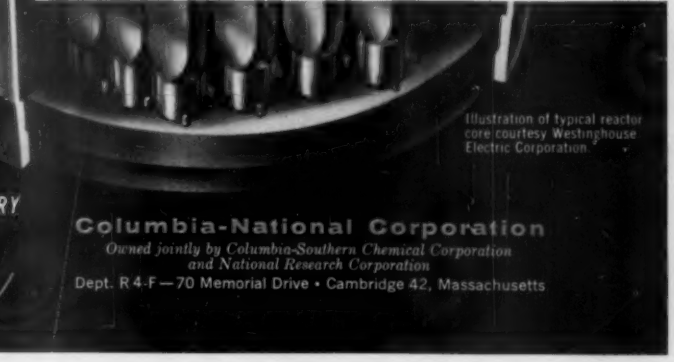

Illustration of typical reactor core courtesy Westinghouse Electric Corporation

NEW METALS FOR INDUSTRY

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Ten years at NDA

Main Headquarters: White Plains, N. Y.

Top—Critical Facility, Pawling, N. Y. Bottom—Radioactive Materials Laboratory, Pawling, N. Y.

NDA is observing its tenth anniversary this month by an activity that has typified its life: expansion—this time to a 63-acre research, development, and technical center at Eastview, N. Y., five miles from present headquarters in White Plains.

By late summer, the new technical center will be NDA's main headquarters. Present facilities in White Plains will then be devoted exclusively to engineering, experimental, and test fabrication activities.

Expansion is underway at NDA-Pawling Laboratories, too, in the form of a new engineering service building and liquid metal test facilities.

Even more important in this ten-year period has been NDA's growth in personnel resources. Its 400-man team encompasses the myriad skills that, knitted together, make an imaginative, mature and responsible organization. This team has one aim: the design, development and production of advanced nuclear reactors for power, propulsion and research.

NDA faces its second decade confident in the knowledge that nuclear reactors will soon see widespread application and firm in its resolve to be a significant part of this essential movement to expand man's energy sources.

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ROUNDUP of Key Developments in Atomic Energy

Budget Bureau Fights AEC Plans; JCAE May Act

The tug-of-war over the nation's civilian power reactor program between AEC and Congress' Joint Committee on Atomic Energy has become a three-way wrangle with AEC in the middle between the Bureau of the Budget and JCAE. The difference of views between AEC and Budget over the amount of money that should be spent on advanced reactor development has held up by almost a month the submission of AEC's fiscal-'59 authorization requests to JCAE.

Meanwhile an impatient Joint Committee is planning the steps it will take to get a five-year reactor development program underway in case none is forthcoming from AEC.

The Commission has made no commitments to JCAE going beyond fiscal '59 except for a program of fuel cycle development (NU, April '58, 17), and continuation by means of new rounds of its Power Demonstration Reactor Program started in January 1955. But the idea of building new types of reactors and successive generations of reactors of tried concepts, which JCAE has espoused, has not gotten past the stage of staff talks.

The AEC staff has prepared a draft, in general terms, of a five-year development plan, but it seems unlikely that the full Commission will put its stamp of approval on it. (Commissioners Vance and Floberg told NUCLEONICS in March that they were opposed to long-term reactor plans at this stage.) So far as is known, the draft has not yet even been up for consideration in a Commission meeting.

But JCAE is determined to have a long-range development program drawn up even if it fails to get one from AEC. Committee plans in that eventuality are to name a select panel of top reactor experts—perhaps three men of the caliber of Henry D. Smyth and Walter Zinn—to assist in drawing up a projected five-year program, have it reviewed first by a broad cross section of industry and then by AEC, take account of constructive suggestions, and adopt it as an official JCAE report for future guidance. This is in line with JCAE Chairman Durham's comment in Chicago in March (speaking of both the '59 and long-range programs) that "if AEC is not able to come up with an adequate program, then the Joint Committee and the Congress must try to fill the gaps."

This of course is not something JCAE expects to accomplish this year, but the Committee does feel the urgency of obtaining an agreement this year on the idea of formulating a longer-range reactor development program.

One thing JCAE feels it has accomplished already is to get AEC to broaden its fuel-cycle program, from one originally geared to water reactors, to an across-the-board approach that would cover high-temperature reactors as well.

Standoff in Executive

While JCAE chafed under the delay in starting the authorization hearings—AEC's authorization requests were due April 10, had not yet been submitted May 5—a battle royal was quietly going on behind the scenes between AEC and the Bureau of the Budget.

AEC is in the middle substantively as well as procedurally: in its debates with JCAE, AEC has taken the more conservative line, contending that the rate of reactor development it has set is adequate and requires no acceleration. But vis-à-vis Budget, AEC is fighting for reactor development projects that it has been pushing, but that Budget wants to pare out of the '59 appropriations. AEC's top leaders have already had several sessions with Maurice Stans, the new Budget Director, that have failed to break a deadlock, and it is believed in Washington that the issue may have to be laid before the President for a decision.

Faced with a whopping $8-billion prospective deficit for fiscal '59, the Budget Bureau—in its role as coordinator of expenditures of all executive agencies for the Administration—is reported taking the line that with first-generation water reactors working well, heavy outlays on gas-cooled and Pu-power dual-purpose units and a proposed 100-Mw heavy-water natural-uranium reactor and others of like nature are luxuries that the country cannot afford in a recession year. AEC has refused to yield and is fighting for Chairman Strauss' philosophy of working on a broadly-diversified range of reactor concepts. Possibly also involved may be some AEC nuclear rocket projects.

Contract awards mark start on PURR, GCRE, APPR-1a

AEC has awarded a $1,025,000 contract to John P. Hopkins Co., Mercer I., Wash., for phase-1 construction of the **Plutonium Recycle Reactor** at Hanford. Hopkins has 425 days to complete the steel containment shell (80 ft dia, 121 ft high, 46 ft below grade), bridge crane, storage and other facilities . . . Peter Kiewit Sons, Omaha, outbid eight others and won the contract, at $4,897,000, to build the conventional facilities of APPR-1a at Ft. Greeley, Alaska. Patterned on the first Army Package Power Reactor at Ft. Belvoir, Va., the Alaskan copy will test feasibility of the plant in an isolated area and yield 42-million btu/hr steam for space heating as well as 1.7-Mw electricity. The basic design is by Alco Products Co., builder of the Ft. Belvoir plant . . . Farnsworth & Chambers Co., Houston, won a contract with a low bid of $1,357,799 to build the control, reactor and equipment building for the **Gas Cooled Reactor Experiment** at AEC's Idaho test station. Seven others bid. The work will take 420 days. Aerojet-General is building and will test-operate the GCRE.

The 100-Mw heavy-water reactor was already in—and knocked out of—the budget a year ago, along with a homogeneous proposal and three small reactors: altogether some $150-million in authorizations was eliminated. This year AEC submitted the big D_2O project again, and again Budget red-lined it. Earlier, at the "harmony" talks this winter between four AEC Commissioners and leading JCAE members, this reactor was cited by AEC as one it wanted to build. The project, on which duPont has done a study for the Commission, bears some relationship to the Carolinas-Virginia Nuclear Power Associates project, a 17-Mw version of the same concept being designed by Westinghouse. However the CVNPA reactor must use enriched fuel, while AEC's big unit would be so designed that it could operate on either natural or enriched uranium.

There are observers on Capitol Hill who feel that, by and large, AEC wouldn't care whether these reactors are publicly or privately built as long as they get built, nor if there were some overlapping of projects; but that the Budget Bureau would care a great deal whether a given reactor type were to be built by a private group such as CVNPA, or by AEC itself. According to this view, Budget would be quite ready to scrap the big project for fear it might interfere with the small one.

AEC is also reported to be trying to get Budget approval for inclusion in its authorization requests of the two reactors laid down by JCAE last fall, on which preliminary studies have just been completed (*see p. 104*): an intermediate, or 40–60-Mw size gas-cooled reactor, now slated to burn slightly enriched rather than natural uranium, and a plutonium production reactor. JCAE sources are confident that "something will go through" on these two reactors, implying that the Committee majority is in a mood to overrule the Budget Bureau if the latter should prevail over AEC.

(In fact, top Budget officials have been invited to testify before JCAE on their action in holding back appropriated atomic energy funds last fall (NU, Jan. '58, 17), and on the criteria they use in passing on current reactor authorizations. They have not yet indicated whether they will accept.)

As April wore on without AEC's authorization requests arriving on Capitol Hill, the Congressional committee began to find other activities hamstrung: for example, it had to postpone *sine die* its scheduled hearings on nuclear waste disposal problems although witnesses had already been assigned dates and times for coming to Washington to testify. Another hearing could not be postponed: Rep. Chet Holifield, chairman of JCAE's subcommittee on authorizing legislation, is also chairman of an Armed Services Committee subgroup on civil defense which had hearings scheduled for late April–early May; and this threatened to enforce another fortnight's delay if the authorizing hearings could not be held earlier.

JCAE therefore began trying to put pressure on Germantown to act, and arranged a meeting between leading members of Committee and Commission to discuss the main outlines of the program and its timing, and to get something up for review.

GAO Forces Withdrawal of AEC Proposal on PAR

Comptroller-General Joseph Campbell blew the whistle on AEC last month, forced it to withdraw its proposal for $25-million in federal aid to Westinghouse and Pennsylvania Power & Light's big homogeneous reactor project. Campbell's objection to both arrangement and manner of the submission to Congress forced AEC to seek a less extensive aid arrangement for PAR (Pennsylvania Advanced Reactor).

AEC is now considering a proposal limited to Phase 1 of the original arrangement ($7-million in research-development assistance from AEC for the 2-year period ending Dec. 31, 1959). The new plan would also attempt to meet objections raised by JCAE Democrats on patent rights. Campbell ruled that the arrangement submitted to JCAE was not a proper one under the third round of the Reactor Demonstration Program. AEC's invitation specifically mentioned the PAR concept as eligible but listed certain conditions for AEC aid, including construction by June 30, 1962.

The invitation explicitly called for proposals "to develop, design, construct, and operate nuclear power plants." Even when it was subsequently extended, Campbell reminded AEC, the third round required completion by June 30, 1963. The third round contemplates, he said, "that proposals be based on an existing belief by proposers in the technological feasibility of projects proposed, whereas [this] proposal clearly admits it will take two more years' research before any determination as to feasibility can be made."

EEI's McAfee Denies Need for Acceleration

J. W. McAfee, president of Edison Electric Institute, lashed out in late March at the proponents of a federally-funded acceleration program for early development of economic nuclear power.

In a surprisingly strong statement, McAfee defended the role of the private utility industry. He told an American Power Conference audience in Chicago that the U. S. reactor program to date has been "an orderly effort based on human intelligence and the proper use of money, materials and men."

"That," he added, "is the approach that has produced the greatest industrial system the world has ever known and there is good reason to suppose that this approach is fully applicable to the development of nuclear power."

McAfee's outspoken defense of the present rate of development was particularly surprising in view of the indication in a recent survey by NUCLEONICS (NU, Feb., '57, 17) that private utility leaders generally support an increase in federal spending on reactor development. More than 20 favored federal subsidy of nuclear fuel.

The EEI spokesman made it clear that he was satisfied with the timing and extent of investment.

"It just so happens," he stressed, "that there is no nuclear reactor that anyone can build today that will give as good an economic result as a modern conventional power plant. What do we have to gain by engaging in a race to produce the greatest quantity of what for us is an uneconomic facility? Let us not waste our strength in racing toward someone else's goal.

"What if fuel availability and cost in other countries justifies a different approach overseas; does that warrant our ignoring our advantages and pursuing a wasteful course here?

"It is possible that building a large quantity of nuclear power capacity would temporarily make an impression abroad. However, the factor which has given us world leadership is the use of our national resources in the most efficient and economical manner to attain superiority in ability to produce."

AEC Staff Opposes Patent Policy Change

AEC's contractors, long upset about federal atomic patent policies, rediscovered last month that they face a tough job in convincing AEC and Congress that the policies should be liberalized.

The occasion: the first public hearing ever held by AEC on the patent provisions of the 1954 Act and the administration of these provisions by AEC. Presiding was AEC's 3-man advisory panel on patents—Casper W. Ooms, John H. Dienner and Jo. Bailey Brown.

The major industry demand: repeal of section 152, which gives AEC title to all inventions or discoveries of its contractors, except where this privilege is waived.

The AEC staff response: Edward Diamond, associate general counsel, and Roland A. Anderson, patent chief, made it clear they oppose any change in section 152 beyond what has already been done administratively to exempt licensees and access-permit holders.

The Ooms panel must present to AEC an "unbiased, objective opinion of patent policies and practices in the atomic energy field." Any change in the law by Congress rests on AEC's decision on whether to recommend such a change.

Short of an outright repeal of section 152, several industry spokesmen insisted, AEC should more often exercise its ability to waive its rights to a contractor's inventions—in advance of the contract.

Other witnesses chided AEC for a lack of aggressiveness in seeking foreign patents for U. S. inventions. The patents may not be claimed by the inventor because AEC has title.

Ooms summed up the day's testimony. With a few exceptions, he pointed out, the industry presentation was marked by "an absence of concrete examples."

"No one seems to know," he observed, "if the Commission's 1,400 patents are just gadgets that anyone can design around, in which case there would be no point in maintaining the present special patent system for atomic energy. Or, on the other hand, if they contain a domineering patent, one that would, if privately-owned, give some company a stranglehold on the industry.

"If there is no domineering patent, what is the point in compulsory licensing to prevent a giant company from becoming a domineering bloc?"

Reactor Progress in France

France's first commercial nuclear power station, EDF-1, being built on the south bank of Loire (top edge of photo above dike) near Chinon by Electricite de France, looked like this at end of March. Basin top right is intake channel; large rectangular foundation at left is turbogenerator building; large circular foundation at right is base of reactor containment sphere. On it are taking shape a smaller circular structure, right—reactor base; and square structure on which will be erected vertical heat exchangers. Exchanger tubes are to be sectionally shielded for easy removal, decontamination and factory repair if required even after reactor has been operating. Carbon-dioxide-cooled 60-Mw(e) unit is to be in service next year

Nuclear Navy: Polaris Sub Already Building; Other News

From Washington, D. C., from Connecticut and from the Gulf Coast came news last month of good progress on the nuclear navy program.

Ballistic sub. General Dynamics' Electric Boat shipyard at Groton, Conn., achieved a significant speed-up of the new FBM (Fleet Ballistic Missile) submarine program (NU, March '58, 23). It announced that work is already well underway on the first of the new-type Polaris-firing subs, as yet unnamed, designated SSN(FBM)598. A number of hull sections already laid down late last year as the *Scorpion*, a *Skipjack*-class attack sub, are being used in the 598 instead, with *Scorpion* temporarily deferred. By this expedient a tremendous jump is gained on 598's construction schedule, with a well-advanced hull in progress a mere two months after the boat was authorized by Congress and assigned by the Navy to EB. The second sub of the class, SSN(FBM)599, will be laid down late this month. Both ships will use the Westinghouse S5W-type pressurized water reactor for motive power.

Attack sub. *Skipjack*, first of the revolutionary high-speed subs combining nuclear power and the *Albacore* tear-drop hull shape, will be launched by Electric Boat May 26. After completion and fitting out, she will join the fleet early next year.

Meanwhile in Pascagoula, Miss., Ingalls Shipbuilding Corp. laid the keel of its second *Skipjack*-class sub, *Snook*. *Sculpin* is already under construction there. And Electric Boat said it would probably make a fresh start on *Scorpion* this summer.

Hunter-killer sub. *Tullibee*, first of the tiny hunter-killer subs, will be laid down this summer by Electric Boat in its north yard, NUCLEONICS learned. It will be powered with Combustion Engineering's vest-pocket pressurized water reactor. The test bed for its land-based prototype, S1C, is already nearing completion—a long yellow horizontal tank structure in a clearing in a remote central-Connecticut forest north of Windsor. This $25-million test facility (adjoining Combustion's new $12-million research and development labs and $4-million core-manufacturing plant) is to be completed by August, and the first core loaded by Dec. 1.

Sodium sub. *Seawolf*, once associated in the public mind with delays, difficulties and superheater leaks, has been setting records for reliability since entering service. Capable of over 20 knots even with a restriction to 80% of design power (the superheaters are sealed off), the big sub has operated 16 months (38,000 mi, 60% of them submerged, 3,650 hrs underway) without a single adjustment to the reactor, without a single entry into the reactor

compartment proper. The core is now half depleted; some time late this year *Seawolf* will be decommissioned, "defueled," the reactor removed and a pressurized-water unit installed. The job will take 15 months to two years.

Destroyer. The Joint Committee reported out a bill providing $35-million for construction by General Electric of the D1G facility—the land-based prototype for a destroyer reactor.

Euratom Talks Success; Ratification Next Step

Racing to get a U. S.-Euratom agreement on nuclear power in being by the end of June, negotiating teams representing both sides early this month worked out an arrangement which they confidently hoped would be ratified without a major hitch.

The agreement, subject to approval by the U. S. Congress and the Euratom Commission, contains these major provisions:

Inspection. The conferees slid past a threatened deadlock on U. S. inspection of reactors built under the agreement by 1. confirming Euratom sovereignty over all nuclear activities within the six nations but 2. providing close cooperation with U. S. technicians from the start. The compromise is designed to provide assurances to the U. S. that no plutonium will find its way into military uses.

Fuel. Enriched uranium will be supplied by the U. S. under long-term guarantees. Net cost to the Euratom countries will be something over the cost of conventional fuel but at attractive prices.

Australia Starts Up HIFAR, First Reactor Down Under

HIFAR, the High-Flux Australian Reactor, went into operation April 18. The Dido-type heavy-water research unit at Lucas Heights near Sydney was built for the Australian AEC by Head, Wrightson & Co. Ltd. of London. HIFAR will also produce radioisotopes.

British Firm Signs to Build First Italian Power Reactor

A contract was signed in London last month under which Britain's Nuclear Power Plant Co. will begin construction of Italy's first nuclear power station, 40 mi south of Rome, within "a few months." The 200-Mw(e) graphite-moderated gas-cooled unit (NU, Dec. '57, 17) is to be completed in 1962.

AEC Indemnity Report Shows Details in Doubt

AEC reported substantial progress last month on a permanent plan to supersede its interim regulation for federal indemnification of hazardous nuclear facilities. But it was made clear that a final program is still some time off.

In a progress report to Congress under the 1957 Price-Anderson Act authorizing indemnity beyond available commercial insurance for nuclear facilities, AEC highlighted:

- Industry will be asked in the near future—probably this month—to comment on a proposed formula for calculating financial protection required for reactors. The formula, which was not ready when AEC made its report to the Joint Committee on Atomic Energy, will be part of a proposed regulation outlining the indemnity plan.
- The Commission has instructed its operations offices to include free federal indemnity in all new operations contracts and to offer the same coverage to present contract operators. Construction contractors would also get coverage where their work involves the risk of a "substantial nuclear incident" (NU, Feb. '58, 27). AEC's contractors will not be required to carry private insurance unless their work is inseparable from commercial work.
- The Commission is still studying possible extension of indemnity to hazardous nuclear facilities other than reactors. Insurance industry representatives have expressed a willingness to furnish liability coverage up to $60-million per facility (the same ceiling as for reactors).
- Under the temporary indemnity regulation in effect since September (NU, Oct. '57, 21), 12 of 22 reactor licensees have filed insurance binders, one insisted he has adequate resources to provide the required amount of financial protection for his facility, and nine (six state universities and three federal agencies) have claimed immunity from tort liability. Accordingly, AEC is 1. considering the need for legislation waiving immunity for such federal reactor operators as the Bethesda Naval Hospital, the Naval Research Laboratory and the Naval Postgraduate School; and 2. working on a model law to permit state-owned reactors to be brought under the indemnity program.

Some idea of AEC's eventual formula for privately-financed protection required by reactor owners emerged from an appendix to the indemnity report. It revealed that a draft formula was drawn up in anticipation of industry advisory group discussions with AEC in December and January.

Major factors in the formula:

Authorized power level: The base amount of financial protection should be calculated by multiplying the reactor power level (in thermal kilowatts) by $150. In case of a reactor of 400 Mw(th) or more, this would be the maximum available commercially—$60-million.

Fuel cycle factor: AEC felt that reactors with large fission product inventories require more financial protection. Thus, the amount of financial protection calculated on the basis of size would be multiplied by a "fuel cycle factor." This was defined as the average number of days equivalent full power operation that a fuel charge remains in the reactor.

Population factor: Under a special formula for figuring population density and location of reactors vis-à-vis populated areas, AEC worked out a factor having this effect: require financial protection for the population within 3-miles of a 1-Mw(th) reactor and within 60-miles of a 400-Mw(th) reactor.

Compromise Solution Seen On Plutonium Buyback

A compromise solution to the plutonium buyback problem looms as a probable result of quiet negotiations between AEC and the Joint Committee on Atomic Energy.

Congressional sources predicted it would run along these lines when formally presented to JCAE as part of AEC's Fiscal '59 authorization bill: 1. For Pu produced in the U. S. or in U. S.-designed reactors abroad, the U. S. would pay $14–16/gm, down considerably from the current price of $30–45/gm for domestically-produced Pu; 2. long-term purchase contracts would run only half the 15-yr period proposed by AEC for Pu produced abroad.

Late in April, the compromise was being drafted into proposed legislation for submission to JCAE under the plant-and-equipment authorization bill of AEC for the fiscal year beginning July 1. As eventually submitted, it was expected to include a special exchange program with Britain: the U. S. would trade one gram of enriched uranium for one gram of British Pu. This would put a price of $16.12/gm on Pu—the price of 20%-enriched U^{235}/gm; Britain Pu price is $14/gm.

Geneva Papers Pouring In, 36 Nations Submit 1,925; Fusion Exhibits, Review Papers to be Innovations

Preparations the world around for the second U. N. Geneva Conference on Peaceful Uses of Atomic Energy are beginning to become feverish as September 1—opening date of the two-week session—approaches.

Up to April 9, 55 of 88 nations invited to participate had accepted; 36 governments had submitted a total of 1,925 titles of scientific papers for presentation. Of these about 900 came from the U. S. alone, culled by 55 special reviewing committees from 1,478 submitted by U. S. scientists. Before the flood at U. N. slackens—it is expected to continue two months past the June 1 deadline for full papers—about 2,400 are expected to reach U. N. headquarters in New York, Sigvard A. Eklund, Conference Secretary-General, believes.

All will be included in the proceedings of the Conference; from the abstracts submitted to date, an international team of 22 scientific secretaries is selecting about 550 to be recommended for oral presentation at the general and technical sessions. In August 1955, there were only 1,067 papers submitted altogether, 450 of which were read.

Final selection of the papers to be honored by reading and discussion will be made by U. N.'s Advisory Committee on Atomic Energy, which will meet this month in Geneva.

As in 1955, there will be both government-sponsored and commercial exhibits, the latter again being in the Geneva Exposition Hall (see map, NU, June '55, 75). The governmental exhibits will be housed in a special exhibit building now being erected on the Palais grounds. Here major efforts are expected to be devoted by the big three to exhibits on fusion—the first time that thermonuclear devices will have been shown to the public.

In the fission field, the U. S. again this year is expected, as of now, to be the only nation to exhibit a working reactor. But instead of one as in 1955, there are to be three: Argonne National Laboratory will have an Argonaut (NU, March '57, 62), and General Dynamics a TRIGA (NU, Nov. '57, 25) in the governmental exhibits, while Atomics International will show its L-77 laboratory reactor (NU, Oct. '56, 98) at the commercial show.

Experiment: Review Papers

Another innovation over 1955 will be the trial on a small scale of review papers—a "new principle, to be very carefully introduced," Eklund cautions. Rapporteurs of technical sessions will be assigned to prepare these reviews on the basis of material presented by speakers from the various countries, and will read them during the conference. However this will be done only in the field of radio-isotopes. It will not be done—at least not this year—for reactors, Eklund explains, since "it becomes very complicated, because you have to take into account the geographic representation of the rapporteurs."

Attesting to the emphasis on fusion at this conference is the scheduling of five or six sessions devoted to the subject—one plenary and three technical sessions on fusion were recommended initially, and one or two more are expected to be added by the advisory committee when the final schedule is drawn up. (Following the 1955 pattern, the first three-and-a-half and the last one-and-a-half days of the two weeks will be given over to plenary or general sessions, with four simultaneous series of technical sessions in between.)

Papers in the field of reactor engineering reflect the great number of reactors completed or begun since the last Geneva Conference three years ago. Just about every significant one is the subject of a descriptive paper.

Gaseous diffusion for isotopic separation of uranium, the technology of which has hitherto been closely held by its sole practitioners—U. S., U. K. and USSR—is on the agenda. The U. S. will offer "Progress in Methods of Isotope Separation for U-235," and France, which has just scored a success in this field, has nine papers on gaseous diffusion (*see p. 25*). Moreover, at least two French papers deal specifically with an even more hush-hush topic: separation of lithium-6 and lithium-7. This process is carried out in the U. S. at Savannah River preliminary to production of lithium-6 deuteride, the source of tritium in the H-bomb.

President of the conference—an honor that went to India's Homi J. Bhabha in 1955—will be Francis Perrin, French High Commissioner for Atomic Energy.

Sweden's Eklund, director of research of the Swedish Atomic Energy Company, is acting in the post held last time by Walter G. Whitman of MIT. His aides are Homi Nusserwanji Sethna of India, Deputy Conference Secretary-General; and Ivan Ulehla of Czechoslovakia, Special Assistant to the Conference Secretary-General.

John H. Martens of Argonne National Laboratory will be chief editor of the proceedings of the conference, expected to run to "more than 30" volumes this year as compared to 16 in 1955.

U.N.'S GENERAL STAFF for the second Geneva Conference shown with the scientific secretaries: (left to right, seated) Valery Ziegler, France; Frank Bruce, U. S.; Ivan D. Rojansky, USSR; Deputy Conference Secretary-general Homi Sethna, India; Conference Secretary-general Sigvard Eklund, Sweden; Special Assistant Ivan Ulehla, Czechoslovakia; Mlle. Renee Bovy, Belgium. (Middle row) Hiroshi Fukunaga, Japan; Frederick Hudswell, U. K.; Claudio Garavaglia, Italy; Chief Editor of Conference Proceedings John Martens, U. S.; Carlos Sanchez del Rio, Spain; Alexander N. Efimov, USSR; Thomas Church, Canada; David Okrent, U. S.; Gavrill S. Strelin, USSR; William Woollen, U. K.; D. Harold Copp, Canada. (Back row) Cesar Sastre, Argentina; Administrative Officer Nathaniel Groby, U. S.; Executive Assistant Brian Urquhart, U. K.; Thomas Coor, U. S.; Pierre Y. Tanguy, France; Liasion Officer for International Atomic Energy Agency Tillette de Mautort, France; Terence E. F. Carr, U. K. Not in photo: three scientific secretaries, from Brazil, Israel, and United Arab Republic

Japan's Atomic Power Program Taking Shape

TOKYO

Japan's atomic power generating program starts taking definite shape in July when three British groups present bids for this country's first power reactor. This step has been a hesitant one despite the fact that Japan, probably more than any other major industrial power, looks toward atomic energy for growth and stability. That is the curious paradox of the Japanese situation: its need for new energy sources is dramatic. Yet, justifiably, the Japanese have been more wary than other peoples of entering the age of nuclear industrial power with whatever hazards may be in store.

The decision to purchase a British Calder-type reactor—taken early this year when a mission surveyed the British atomic scene—capped an already carefully-mapped-out program of building research reactors (see Tables 1, 2). It was made, in principle, in 1956 when a British mission visited Japan. But there has been considerable disagreement among Japanese atomic power interests about the project. Opposition to the Calder Hall project exists on two levels—from some private industrial sources which prefer to move quickly into a program tied to U. S. sources of technology, and from part of the Japanese scientific community which objects altogether to a dependence on technology from foreign countries and which would prefer to pursue its own pattern of development—even at the risk of its being relatively slow.

In the end, the Calder-type purchase was decided for three reasons:

1. A general conviction among many people inside the Japanese government's atomic setup and in private industry that the British reactor is a proved producer while American power reactors are still in the "experimental" stage. The Japanese believe this is true simply because the U. S. does not need nuclear power to the same extent that Britain—and Japan—need it now as a source of new energy.

2. The commitment made, at least in principle, by Matsutaro Shoriki, Japan's atomic czar, to buy a British reactor could not be voided. There is a strong belief—at least in U. S. circles—that Shoriki's advisers may now have second thoughts about the Calder-type reactor, but there is now a question of "face" involved.

3. The fact that the Calder type uses natural uranium (or slightly enriched in the modified version which will probably be built here) has been a come-on for the Japanese.

The timetable for the Calder Hall reactor is elastic but the Japanese hope to decide on the contractor by fall, negotiate through the winter, then actually let the contracts in early 1959. The reactor will take about four years to construct.

Second Reactor from U. S.

Meanwhile, a second power reactor will probably be ordered from the U. S. But it's doubtful whether the Japan Atomic Power Co. (the amalgamation of private and public companies which heads the power program) will be able to handle negotiations for a second reactor before the British project is somewhat cleared away.

Another problem for Japanese reactor purchases—whether from Britain or the U. S.—is the lack of a bilateral treaty covering atomic information with either country. Negotiations with the British, well advanced, are held up on several points. The Japanese were asking for third-party insurance which the British have not been willing to give. That problem apparently has still not been solved. However, the problem of how fuel would be handled has been, since the Japanese A.E.C. has now decided that it will import all fuel itself rather than allow the private trading companies to be importers. In the latter case, the British would have had to police the companies—a procedure which the Japanese, super-sensitive about their sovereignty, could not allow. Negotiations with the Americans for a bilateral are also well-advanced. But whether it can be initialed, presented to Congress for the required waiting period, and to the Japanese Diet before Japanese elections are called and the Diet dissolved, remains problematical.

Jungle of Relationships

Behind these negotiations at government-to-government level is a jungle of conflicting private interests within the country. The major Japanese companies, clearly seeing the great future of atomic energy in this country, have tried to get into the act. But the old Japanese problems of capital shortage, lack of technology and administrative ability, and the need to maneuver in government circles, has dictated a peculiar lineup.

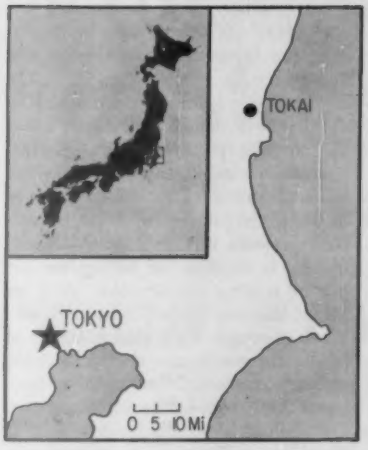
Five atomic "groups" have been formed. By and large, they represent configurations of the traditional Japanese company groups—the postwar version of the prewar Zaibatsu which once practically controlled all Japanese banking, manufacturing, and trade. Each is headed by a heavy electrical producer (except the Sumitomo group which plans to act as a collaborator with one of the other groups, supplying no reactors but working with fuel and isotopes). These groups have traditional alliances with foreign companies.

Directing the national research

TABLE 1—Japan's Research Reactor Program*

Type	*Status*	*Purposes*	*Builder*
JRR-1 (water boiler)	Operational Aug. 1957	Exponential for JRR-3, basic research, short-life-isotope production, training	Atomics International
JRR-2 (CP-5 type)	JAERI under construction	Material testing, basic research, limited isotope production	AMF, Mitsubishi group
JRR-3 (heavy water type)	JAERI contracts let	Experience in design & construction, basic research, engineering tests, isotope production	Primarily Japanese with small foreign participation. AMF, Combustion Engineering known to be bidding
Materials Testing Reactor probably JMTR-4	Planning stage	Materials testing, engineering tests	?
Experimental power reactor JRR-5 (10 Mw)	Planning stage	Experimental power production	Probably from U. S.
Research reactor (swimming pool type)	Planning stage	Basic research, isotopes	?

* All reactors operated by JAERI, except the last which will be operated by Kyoto Univ.



effort is Japan Atomic Energy Research Institute (JAERI), a joint government-private enterprise outfit. Its labs are about 40 mi north of Tokyo in a little village, Tokai, bordering on a U. S. artillery range that JAERI eventually hopes to acquire for expansion. The first two research reactors are located there, and the first power reactor will probably also be located nearby.

The government is footing most of the bill for JAERI's activities (1958 budget totaled ¥4,842,810,000 ($13.5-million) of which less than 10% was contributed by private firms). The private contributions come from the whole gamut of Japanese industry—utilities, iron and steel companies, coal producing outfits, petroleum companies, and the heavy electrical manufacturers. The Institute has also begun to earn some money from the sale of isotopes, and other pile by-products.

The program of development of the J.A.E.C. and the Science & Technology Agency aims toward a gradual increase in the participation of Japanese companies as reactors are built. Thus the first research reactor was designed and built for JAERI almost exclusively by Atomics International. The second research reactor is being designed and constructed by American Machine & Foundry, but important locally-built components are being supplied by the Mitsubishi atomic group. The third research reactor to be built for JAERI will be largely a Japanese operation with all five atomic groups taking part in its construction. The divvying up of this project is now underway.

Companies' U. S. Ties

It was, in fact, the possibility of considerable local manufacture of components for a Calder Hall reactor that contributed to the decision to build a British before an American unit. However, only one of the Japanese atomic groups—the Hitachi group—has a past relationship with one of the British groups bidding on the power reactor: Hitachi is a licensee of Babcock & Wilcox for boiler manufacture.

On the U. S. side, Mitsubishi has a long history of close affiliations with Westinghouse. It applied more than a year ago to the Ministry of International Trade & Industry for approval of an atomic licensing agreement with Westinghouse (NU, Aug. '57, 19; Nov., 18). But MITI has not given approval, shows no signs of it. The government's policy, apparently, is to hold up long-range commitments until it has a more definite idea of which U. S. companies will take long-term atomic leadership.

Another interesting situation is posed by General Electric's relationship to Tokyo Shibaura (Toshiba) and Hitachi. Prewar GE was a substantial stockholder in Toshiba and Toshiba is generally known as GE's licensee in Japan. But after the war, GE moved to license Hitachi for certain heavy electrical equipment items as part of its worldwide program to escape accusations of cartel agreements. Now spokesmen for both Toshiba and Hitachi say they will represent GE if and when GE-designed reactors become a factor in Japan's atomic energy program.

How fast these Japanese companies move toward effecting alliances with the U. S. companies in the atomic energy field will depend on many factors. The need is obvious. Latest estimates by Japanese planners predict that Japan's demand for electricity will increase from 61.1-billion kwh in 1956 to 101.9-billion in 1962, to 185-billion in 1975.

Power Expansion

Japanese companies have scheduled a total capacity of 29.3-million kw—including 15.5-million kw of thermal power—to be exploited by 1975. Such expansion of power sources would call for the equivalent of 45.3-million tons of coal. With her petroleum bill already running near $280-million for imports, or 10% of the total foreign exchange budget, Japan must make the most economical use of her limited capital. Several recent excursions into Middle East have thus far failed to provide concrete results; in any case a Japanese government must consider carefully the kind of capital investments required even for "cheap" Middle East oil in the face of that area's political instability. Yet by 1975, if present trends prevail, Japan will have to depend on foreign sources for 48% of the equivalent of the 271-million tons of coal it will

TABLE 2—Organization of Government Atomic Program

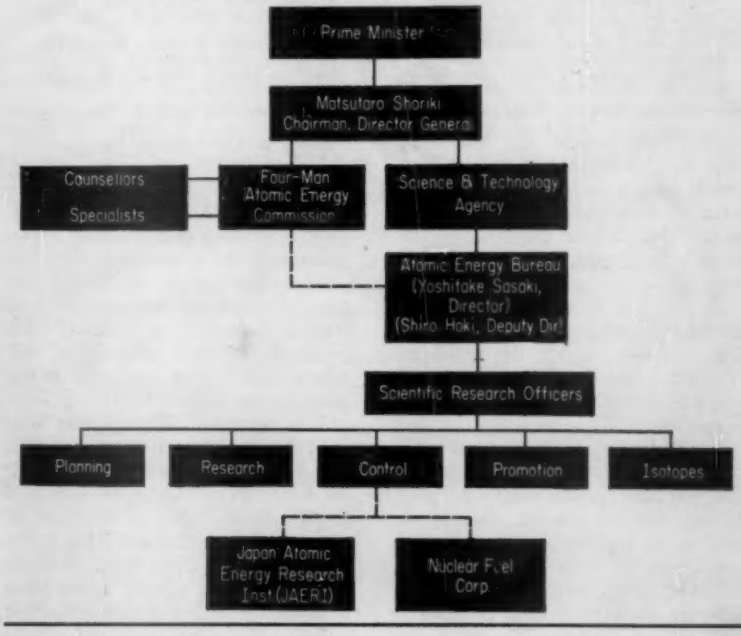
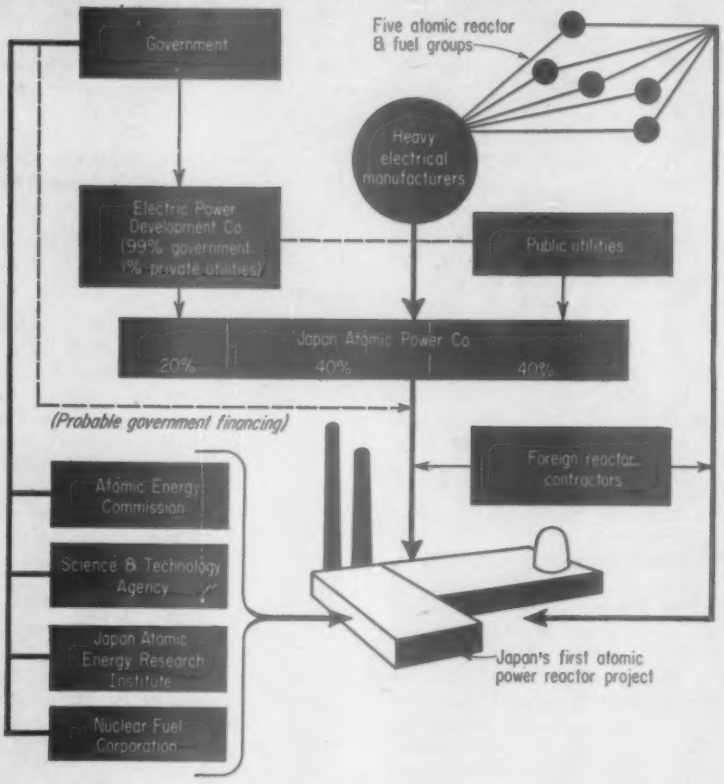


TABLE 3—Relationships in Developing Japanese Atomic Power



Japan's Five Atomic Power Groups.

Mitsubishi Atomic Power Industries, Inc. (Mitsubishi group). Mitsubishi Electric Mfg. Co., Ltd., Mitsubishi Shoji Kaisha, Ltd., Mitsubishi Metal Mining Co., Ltd., Mitsubishi Nippon Heavy-Industries, Ltd., Mitsubishi Heavy-Industries, Reorganized, Ltd., Mitsubishi Shipbuilding & Engineering Co., Ltd. Mitsubishi Chemical Industries Ltd., Mitsubishi Rayon Co., Ltd., Asahi Glass Co., Ltd., and 16 other Mitsubishi concerns.

Nippon Atomic Energy Industry Group (NAIG) (Toshiba-Mitsui group). Tokyo Shibaura Electric Co., Ltd., Daiichi Bussan Kaisha, Ltd., Ishikawajima Heavy Industries Co., Ltd., The Mitsui Bank, Ltd., Mitsui Shipbuilding & Engineering Co., Ltd., Toyo Rayon Co., Ltd., and 26 other companies.

Tokyo Atomic Industrial Conference (TAIC) (Hitachi group). Hitachi, Ltd., Showa Denko, K. K., Hitachi Shipbuilding Engineering Co., Ltd., Nippon Mining Co., Ltd., The Fuji Bank Ltd., The Sanwa Bank Ltd., and 12 other companies.

First Atomic Power Industry Group (FAPIG) (Furukawa group). Furukawa Electric Co., Ltd., Kawasaki Aircraft Co., Ltd., Dai-ichi Bank, Ltd., and 11 other companies.

Sumitomo Atomic Energy Committee (SAEC) (Sumitomo group). Nippon Electric Co., Ltd., Sumitomo Atomic Research Co., and 12 other Sumitomo companies.

need. That is why the Japanese look at the economics of nuclear power with a considerably different point of view than American planners. This is the background for Japan's long-term, essentially four-point plan:

1. Building as early as possible a Calder-type reactor;

2. Building a U. S. enriched-uranium, water-cooled reactor to produce half the atomic generated power by 1965.

3. Gradually promoting a program of Japanese manufacture so that by 1967 Japan would be producing 93% of reactor equipment used in this country.

4. Parallel with the domestic manufacturing plan, inaugurating a program, through JAERI, to build a breeder power reactor for commercial use by 1970.

This is obviously an ambitious program in terms of capital expenditure, technology, and planning. The Japanese hope to overcome the first problem through the traditional pattern of Japanese government and private industry cooperation. Indeed, it is often difficult to tell where one begins and where the other leaves off (see Table 3).

The Japanese also hope for help from the British and the Americans. The Calder-type power reactor will be built, they hope, by extensive credits from Britain. A total of about ¥3-billion ($8,333,333) is the estimated cost at this time of about one-third of the reactor to be built in Britain. An additional ¥5-billion ($11.1-million) will be needed for fuel costs. The rest of the capital cost, the Japanese hope, can be met in yen locally.

There is, of course, no doubt that the Japanese will have to lean heavily on foreign firms for technical assistance during the early part of their program. But the experience of U. S. engineers involved in current projects is that Japanese technology is capable of taking on the job of reactor construction after an initial training period. Indeed, one U. S. engineer feels that because of low Japanese labor costs, his machinery is often fitted with components and installed with more care and skill than would be available in the West. Trained physicists at a higher level are harder to come by.

AEC Boosts U Buying; May Authorize Export

The Administration, trying to head off Congressional intervention in the uranium milling crisis (NU, March '58, 22), last month took two steps to ease the pressure for an expensive government stockpiling program.

With the consent of the Budget Bureau, AEC partially reopened the door it had closed last October to the construction of new milling capacity, then renewed its promise to take a sympathetic look at the possibility of cancelling the embargo on uranium exports under appropriate safeguarding.

The sole purchaser of U. S.-produced uranium oxide, AEC suddenly found itself last year with all the oxide it needed and, with the Budget Bureau breathing down its neck, declared a moratorium on new purchase commitments. The stop-order brought protests both from that portion of the industry which had gone too far to stop and from industry spokesmen in Congress.

Under the threat of action by the Joint Committee on Atomic Energy, AEC conducted a study of the industry's problem areas and reported to JCAE that it was preparing to take on additional purchase commitments equivalent to 3,300 tons per day of new U milling capacity—and perhaps a little more eventually to meet further inequities. Mining areas cleared for the new mill construction were: southeast Texas, 600 tons/day; North and South Dakota, 600; Wyoming, 1,700; Colorado front range, 200; and Nevada (Austin), 200.

World News

Japanese Firm Enters World Graphite Market

Showa Denko Kabushiki Kaisha, a leading Japanese chemical, aluminum and graphite firm, is ready to enter the world market for reactor graphite. Tatsuo Saito, managing director, will explore sales potentials during a trip this month to the U. S. and Britain. He says the company's product has been certified for reactor use by both countries and France.

Japanese Seeking Fuel in Thailand, U. S.

Komatsu Seisakujo, a Japanese scientific equipment and weapons manufacturer, will exploit Thailand deposits of monazite to produce thorium oxide, cesium and other rare elements, and is planning a pilot plant there. The firm has also prospected for Thai uranium (NU, Feb. '57, R11). . . . Japan is negotiating for seven tons of enriched uranium from the U. S. to fuel U. S.-designed research reactors, Japanese State Minister Matsutaro Shoriki revealed.

France's EL-3 Reaches Full Power

The $10-million research reactor EL-3 at Saclay, France's nuclear research center, has attained its design output of 10-Mw(th). The high-flux (8×10^{14}) materials testing reactor went critical last July (NU, July '57, 27), will also make isotopes. It is fueled with slightly-enriched uranium from Britain, moderated and cooled with heavy water from the U. S.

ENEA Considers Reactor in Britain

Under sponsorship of OEEC's European Nuclear Energy Agency, a meeting of top nuclear scientists (with Euratom also represented) last month studied a British offer for joint construction of an experimental reactor in the U. K.; a recommendation is due by June 1. Also studied: the plan for ENEA to take over operation of Norway's new boiling reactor at Halden (NU, Jan. '58, 21); this is to be settled by further talks in Oslo.

Two British Consortia in Deal

Babcock & Wilcox Ltd., a leading member of one of Britain's four original nuclear power-station-building syndicates, has signed an agreement to design, manufacture and erect reactor pressure vessels for the fifth consortium, Atomic Power Constructions (NU, Feb. '57, R11).

France Going Ahead on Diffusion Plant

Long under consideration (NU, May '57, 21), France's plans to build her own gaseous diffusion plant for enriching uranium are reportedly moving ahead. The move follows an unpublicized rejection last December by Euratom of a French proposal for joint construction of a European separation plant. Germany and the Benelux countries protested the project was too costly and that European needs for enriched U could be supplied cheaper from the U. S. Italy, on the other hand, reportedly agreed to help finance the French project, and would get 5–10% of the facility's output. In France, too, there is opposition from those who feel the cost of a diffusion plant—unofficially believed to be about $60-million—is too great a strain on France's economy. But those who feel France must have her own source of U^{235}—whatever the cost—to be industrially and militarily independent now have the upper hand, and informed sources say a decision will be made in July on the site for a plant capable of handling 500 tons of natural uranium. Supporting this trend is the success of French efforts—independently, without U. S. or British information—to achieve uranium separation by gaseous diffusion, in a pilot cell at Saclay. This is believed to use a new, unknown membrane material just as effective as ceramic but "a good deal" cheaper. The pilot cell has been working since late 1957; eleven more are nearing completion to verify cell series circulation and output.

Harwell Unveils Homogeneous Critical

Hazel (Homogeneous Assembly, Zero Energy) has been placed in operation at Harwell. Hazel uses enriched uranyl fluoride as fuel; the salt is suspended in heavy-water moderator. An earlier Harwell system, ZETR (Zero Energy Thermal Reactor), was used to study fuel suspended in light water.

Dutch Plan Agricultural Reactor

The Netherlands has decided to build a research reactor, for operation in 1961, to study the life-processes of plants and animals and to advance agricultural technology. Operator will be the Institute for the Application of Nuclear Energy in Agriculture at Wageningen near Arnhem.

Venezuela, Australia Put Isotopes to Work

Venezuela has hired Nuclear Science & Engineering Co., Pittsburgh, to trace the drift of silt and sand at a prospective port site—Moran, on Golfo Triste. The firm will use radioactive scandium oxide during a two-month study to determine whether the silt is controllable and, if so, where to place breakwaters . . . Australia is using radioactive iodine mixed with stable iodine to gage the size need for artificial lakes to cool huge coal-fired power stations—up to 1,000 Mw(e).

'Many Tenders' for Gas Reactor, Briton Says

"Practically every country in the world is interested" in the U. K.'s gas-cooled, graphite-moderated reactor, A. L. G. Lindley, an official of General Electric Co. of England, asserts. He reports "many inquiries" seeking tenders for complete power stations within the next six months, with 5–6 already in the active discussion stage. GEC has recently completed an expansion of its research-development facilities at Erith, Kent. New facilities include a beryllium lab to exploit the potential of Be for fuel cladding at temperatures over 1,100° F.

Canada, Switzerland Sign Bilateral

Canada and Switzerland have signed an agreement clearing the way for exchange of nuclear information, mutual access to installations, sales of materials and equipment, and eventual Swiss purchase of Canadian uranium. Ratification by the Swiss Parliament is expected routinely. . . . Switzerland has added $2.5-million to its 1958 nuclear research program plus another $1.1-million for lab equipment for the nuclear research center at Würenlingen. Later this year Berne will consider a 5-year, nuclear development plan now under study.

ACF Gets License for Swedish Reactor

AEC gave notice last month that it would license ACF Industries about May 10 to ship a 30 Mw(th) testing-research reactor for Sweden's Atomic Energy Co.

ROUNDUP

Reactor News

LATE REACTOR NEWS HIGHLIGHTS

AEC has approved as a basis for contract negotiations the proposal of Carolinas-Virginia Nuclear Power Associates for a 17-Mw(e) heavy water reactor . . . The Engineering Test Reactor, after initial troubles (NU, Jan. '58, 102), is now operating at full design power level, 175 Mw(th). . . . American & Foreign Power Co. has indefinitely postponed plans to set up two GE boiling water reactors and an Atomics International organic moderated reactor in Brazil, Cuba and Mexico. A&FP told JCAE original cost estimates were "far too low." . . . AEC has lifted its 20% enrichment ceiling on uranium shipped abroad for research reactors, will "consider requests for highly-enriched fuel."

THIRD PRIVATE TEST REACTOR SET . . .

A third privately-owned test reactor was scheduled last month by Industrial Testing Reactors, Inc. The newly-formed Charlotte, N. C., firm said it would begin construction by about July 1 on a $12-million, 50-Mw(th) light-water test reactor, located on a 15-acre site 12 mi east of Wadesboro, N. C., on the Pee Dee river. General Electric will supply the reactor; J. A. Jones Construction Co. of Charlotte, whose president is one of five founders of ITR, is general contractor, and Ralph M. Parsons Co., Los Angeles, will serve as consulting engineer. The Jones firm has been interested in building a testing reactor for a long time (NU, Aug. '55, 10). Target date for start of operations is April 1960. Similar to but larger than GE's GETR, now building at Vallecitos, reactor will have a fully-enriched, 31-plate core in a pool serving as shield and coolant; irradiation facilities will be provided both in the core and the pool. ITR estimates another $8-million will be spent for special auxiliary facilities to be built on adjacent land leased to reactor users.

. . . AS TWO EARLIER ONES ADVANCE

GE has received an AEC construction permit for its 30-Mw(th) test reactor, GETR, as well as an allocation of 154 kg fully-enriched uranium. Westinghouse has assigned Holmes & Narver, Los Angeles, to conduct a hazards evaluation study of its 20-Mw(th) test reactor, WTR, now going up at Waltz Mill, Pa., near Pittsburgh. The study will cover vessel rupture, chemical reactions, origin of forces and their magnitude, and structural and site analysis.

FUEL LEAK FORCES SHUTDOWN OF HRE-2

AEC's Homogeneous Reactor Experiment No. 2 at Oak Ridge was shut down for repairs last month shortly after having been brought to 5-Mw(th) full power when "fuel from the main core system was found to be transferring to the blanket heavy-water system." Oak Ridge Lab Director Alvin Weinberg told the Joint Committee that HRE-2 had run at full power for a whole week, and "somewhat exceeded the full design power of 5 Mw(e)"; it "behaved beautifully," he said, until "we noticed that the level of the fuel in the main circulating system suddenly began to drop." Investigation showed there is a leak in the inner zirconium vessel in the neighborhood of a welded section. Oak Ridge now will run HRE-2 as a single-region system with core and blanket regions mixed, but its hopes to demonstrate homogeneous breeding appear to be doomed for now: Weinberg told JCAE, "We were disappointed that this first zirconium tank ever built proved to have such a short life."

DRESDEN SAFETY SPHERE PASSES TESTS

The 190-ft containment sphere at Dresden has passed its pressure tests and two temporary openings have been cut for passage of material and equipment. The 1.4-in. thick, 3,500-ton shell was filled with compressed air to 37 psi—25% above design pressure of 29.5 psi.

TRAINING REACTOR FIELD ACTIVE

Aerojet-General Nucleonics shipped its first AGN-211, which it calls the first portable pool-type reactor, to the Brussels Fair by airfreight. It is on loan to AEC for seven months. Capable of operating at 100 watts continuously, at 1 kw intermittently, the AGN-211 first went critical Feb. 13 with only 780 gm contained U^{235}. . . . ACF Industries unveiled its Model 605 training reactor, second in a new line of low-power pool units. The first, introduced last fall (NU, Dec. '57, 25), has a power of up to 10 watts; the second, up to 10-Kw(th). The 605 is expected to cost $180,000–185,000 installed including shielding and instrumentation, requires only standard utilities, and can be installed in existing buildings with only special footings for the concrete shielding needed. . . . Minneapolis-Honeywell has sold four reactor simulators to West Virginia, Minnesota, Oklahoma and Wayne State (Detroit) universities.

SRE CORE-LOADING EXPERIMENTS PLANNED

An elaborate core testing program for the Sodium Reactor Experiment has been worked out, to develop high-performance fuel elements that will cut operating costs in large sodium power plants. Present loading is ~3,000 kg uranium, 2.78% enriched; criticality was reached with 33 elements but power tests to date have used the full loading of 43 elements. The thorium-uranium alloys are to be tested for thermal breeding feasibility as well as pushed to 1,800° F in metallurgical and radiation-damage tests. A new loading of 30 elements of 7.6% (wt) Th-U, similar to the present elements but with simplified hardware, and seven experimental elements of 2.78%-enriched U, will be inserted late this year.

FORMOSA BUYS GE RESEARCH REACTOR

General Electric will install a 1-Mw(th) pool research reactor early next year at National Tsing-Hua Univ., Taipei, Taiwan (Formosa). The reactor will use 20%-enriched uranium, with the core suspended from a bridge movable to either of two pools. Similar to the pools GE is building for Spain and Venezuela, it is to be completed early in 1959.

GE COMPLETES FUEL-ELEMENT EXPANSION

General Electric's Atomic Power Equipment dept. has completed a $1.5-million addition to its nuclear fuel production facilities, San Jose. The new facility, capable of producing 300,000 uranium oxide pellets a month, gives APED separate fuel-element plants for power and research reactors. Total investment in the fuel plants is now $2.5-million.

FLYING REACTOR MOVED TO OAK RIDGE

The world's first flying reactor, the 1-Mw Convair portable pool installed in a B-36 bomber for shielding tests (NU, Jan. '58, p. 58), has been transferred to Oak Ridge where it will be hung from the 300-ft towers of the Tower Test Facility. There it will serve in a study of radiation patterns, for use in designing crew compartments of nuclear planes.

News in Brief

AEC's Isotope Prices Slashed 90–99%

The price reductions announced by AEC in March (NU, April '58, 24), made possible by greater anticipated production at the new Oak Ridge Multicurie Fission Product plant, cut costs sharply from those formerly in effect. Cesium-137 is cut from $14 to $1–$2 per curie; promethium-147 from $500 to $1.75–3.25; cerium-144 from $1,000 to $1–2; strontium-90 from $500 to $5–10; technetium-99, formerly $1,000 per millicurie, is now $80–140/mc.

Action Taken on Nuclear Icebreaker, Cargo Sub

The House Merchant Marine Committee has authorized construction of a nuclear-powered icebreaker for the U. S. Coast Guard; next steps would be consideration by the House itself and the Senate, then a similar round of votes on initial appropriations . . . The Maritime Administration has awarded Aerojet-General Nucleonics a $36,620 research and development contract looking toward possible construction of a subsurface cargo ship, employing water-jet propulsion. Demonstration of this propulsion system would be followed by an adaptation study of nuclear power for the craft. The Aerojet contract covers first-phase study only.

7 Lines Seek to Run *Savannah*; Simulator Bought

United States Lines, Moore-McCormack Lines and American President Lines were among the seven shipping firms that have expressed interest in operating the N.S. *Savannah* when she goes into operation in 1960 (NU, April '58, 27). The other lines are Farrell, Pacific-Far East, Isbrandtsen and States Marine . . . Meanwhile Westinghouse got a $180,230 contract from the Maritime Administration to design and build an electronic simulator of a nuclear ship-propulsion system, for training *Savannah's* crew. Twelve firms bid. The machine, to be delivered in April 1960, will also be used for study and training in connection with later nuclear merchant ships. Savannah's keel will be laid May 22. Meanwhile AEC approved as basis for negotiations a proposal by General Electric to develop an improved second core for *Savannah*. The 18–24-month development and fabrication job would cost an estimated $1.8-million. The second core will serve as a spare, later replace the first core. Work is expected to start at once in GE's San Jose plant.

ANS Gets New HQ, New Secretary

The American Nuclear Society is moving its headquarters from Oak Ridge to Chicago July 1, where it will be housed in the John Crerar Library (86 E. Randolph St.), an AEC repository library for atomic literature. Having grown to 3,000 members since incorporation in June 1955, ANS felt the need of a more central location. Octave J. DuTemple has been named ANS' first full-time executive secretary. The Argonne chemical engineer replaces W. W. Grigorieff, who had served as part-time secretary and who leaves for a post with the International Agency in Vienna.

Atom Attracts New Firms, Others Expand

American Bearing, Indianapolis, entering the fuel-element research and production business, is a bidder to supply the fuel elements for Power Reactor Development Co.'s Fermi reactor . . . Wesson Metal Corp., Louisville, plans a $500,000 metals research lab for work on nuclear devices for missiles . . . Varian Associates, Palo Alto, has formed a radiation division "geared to become a major manufacturer" in the field of particle accelerators . . . Rocket-Valve Corp., Denver, intends to invest $500,000-plus this year in lab and production equipment to design and manufacture low temperature valves for the nuclear aircraft, missile and oil industries.

Texas U. Studying Crude Oil Irradiation

George W. Crawford, Texas Univ. physicist, is directing a research effort to reduce the viscosity of crude oil by low-level cobalt irradiation. Object: to convert heavy underground crude (up to 1,000× heavier than normal crude) into oil light enough to be pumped to the surface. The long-term lab program will try to establish how long it takes to lighten oil.

PG&E to Nuclear Power by 1965?

Much of the thermal capacity built by his company to produce electricity after 1965 will be nuclear, predicted Walter Dreyer, vice president and chief engineer of Pacific Gas & Electric, at a management seminar on the economic potential of atomics in Northern California.

AEC Donates 32-Mev Accelerator to USC

The U. of Southern California will take title this month to the $1-million, 32-Mev proton linear accelerator built for AEC by the Univ. of California Radiation Laboratory, Berkeley branch. The transfer comes after months of preparation at the USC campus.

AEC Names New Research Head

John H. Williams, Minnesota Univ. physicist, has been named head of AEC's Research Division, a post vacant since Thomas H. Johnson resigned Oct. 1. (Eugene Booth had been named but could not take the job: NU, March '58, 18). Williams is director of the proton linear accelerator project conducted at Minnesota Univ. for AEC, and a former president of Midwestern Universities Research Assn. (MURA).

Food Irradiation Program Moves on Two Fronts

A 2-million-curie cobalt-60 gamma facility, designated HI-FI (for High Intensity Food Irradiator), will be built by AEC and the Defense Dept. at the projected Army radiation center at Sharpe General Depot, Lathrop, Calif. Proposals to build the machine are due May 16. The facility, which replaces FIR (Food Irradiation Reactor) dropped in October (NU, Nov. '57, 22), is in addition to a linear accelerator Varian is building. The center is to be completed by mid-1960. . . . AEC's Savannah River plant, operated by duPont, has entered the food irradiation program: it will expose food to spent fuel-element gammas for the Army Quartermaster Corps.

World Instrument Market—$47-Million in 1958?

The world market for nuclear instruments this year is estimated at $47-million by Ernest H. Wakefield, president of Radiation Counter Laboratories—U. S., $40-million; U. K., $3-million; continental Europe, $2.5-million; Japan, $800,000; Canada, $300,000; rest of free world, $400,000.

ANS Plans First West Coast Session

The American Nuclear Society will hold its fourth annual meeting—its first on the West Coast—in Los Angeles, June 2–5 (Statler Hotel). Some 190 papers will be presented at 24 sessions; special sessions include one on radiation damage in metallic fuels, another on shielding.

Work-in-Progress Curve Refined, Revised

A revised and refined set of curves showing expenditures for civilian atomic energy development are presented this month by NUCLEONICS.

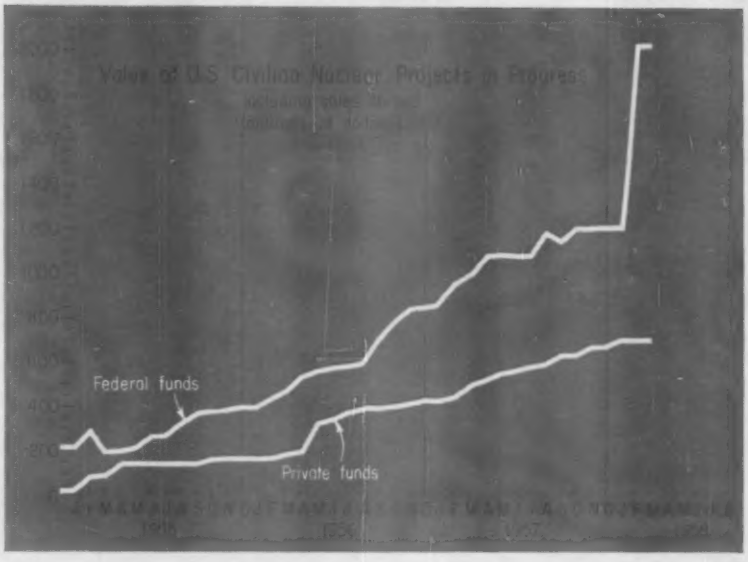
The job of refining has been underway intensively for more than four months. The curve previously shown was based on figures supplied by *Construction Daily;* these were quite highly accurate, but reflected certain differences of interest between that publication and NUCLEONICS.

The new curves at right separate Federal and private expenditures. The former includes ANP costs, and the Navy program which accounts in large part for the steep rise of the curve in recent months. The latter totals private funds spent for civilian atomic energy regardless of whether an amount represent income to a given company (like sale of a research reactor) or expense (like building a private critical facility). Research-development expenses are included only when they are part of a specific project that has reached construction stage: thus, for example, research-development money spent for Shippingport is included, but paper studies on gas-cooled reactor projects are not. The entire initially-estimated cost of a project is entered at the month when construction begins; incremental costs, if any, are added when they become known, and total cost is subtracted in the month of completion. Thus the curves represent total value of projects in progress.

As all workers on industrial statistics will recognize, 100% complete and perfect statistics in this field are an ideal to be approached but never attained, unlike such relatively simple factual statistics as automobile deaths or temperature and rainfall. Companies keep books on a divisional, not topical basis; they are reluctant to publish figures, for competitive reasons; AEC regularly uses operating-budget funds for fabrication and minor construction; and a host of other similar considerations makes nearly every project a problem. Nevertheless NUCLEONICS presents these curves with confidence that they represent a faithful mirror of the growth of the civilian atomic industry. We will continue our effort to improve and refine these statistics, and we invite reader comment on their usefulness.

—The Editors

NUCLEONICS Statistics of the Month



	Latest month	Month ago	Year ago
Nuclear Contracts*—			
Contracts awarded for federal projects ($10³)	20,407	2,455	3,729
Proposed construction, privately-owned ($10³)	0	22,500	0
Contracts awarded, private work ($10³)	0	0	1,000
Backlog of private projects ($10⁶)	269	269	175
Access Permits†—			
Access permits issued	24	12	46
Total access permit holders	1,411	1,402	1,249
Isotope Use†—			
Applications for isotope use	564	328	444
Cumulative total of isotope users	3,587	3,512	3,889
Oak Ridge National Laboratory shipments	1,300	1,162	1,284
Public and private export shipments	449	252	185
Employment†—			
AEC employment	6,831	6,787	6,650
Construction and design contractors' employment	9,973	10,181	14,143
Total operating contractors' employment	100,559	100,067	94,520
Production workers	50,516	50,229	50,652
Research and development employees	43,980	43,651	38,128
Miscellaneous workers	6,063	6,117	5,740

	Operating	Building	Contracted
U. S.-built Reactors‡—			
Power, domestic	1	5	8
Power, for export	0	1	2
Power experiments and pilot plants	7	4	2
Military and naval	5	21	12
Research and test, domestic	43	24	39
Research and test, for export	7	14	4
Foreign-built Reactors‡—			
Power, domestic	4	24	12
Power, for export	0	0	2
Research and test, domestic	25	18	8
Research and test, for export	4	8	1

* From *Construction Daily*, a McGraw-Hill periodical †From AEC ‡ NUCLEONICS figures

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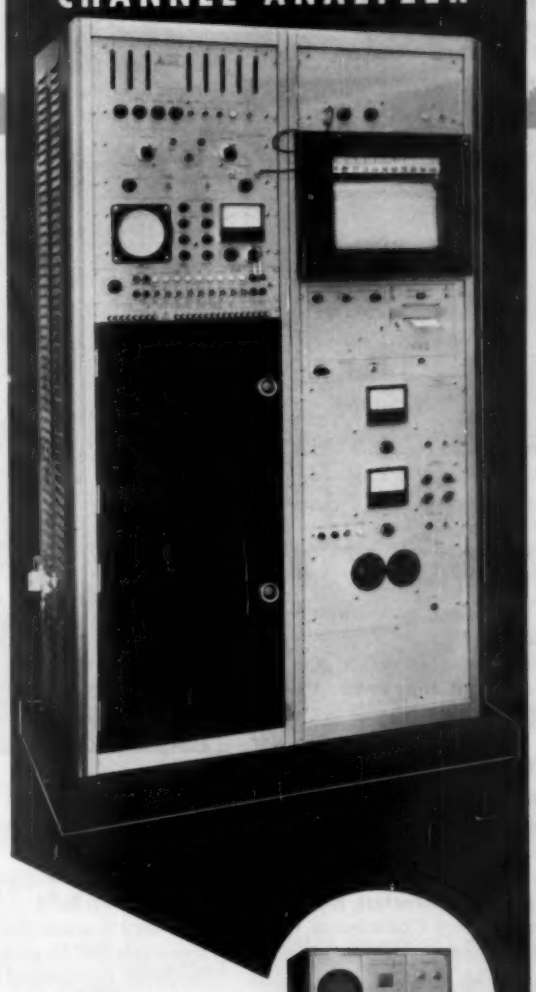

• We surveyed multi-channel analyzer users to find out what they wanted in an analyzer. The results of this survey, combined with our years of research and manufacturing experience in the multi-channel analyzer field, have enabled us to produce what we consider the finest analyzer on the market today—the improved RCL 256.

Our customers not only helped us develop the RCL 256 but also this ad—much of which is composed of excerpts from our survey of current RCL 256 users.

Typical Uses of the RCL 256*

" . . . low level gamma counting . . . fission product and fallout analysis . . . alpha pulse spectrometry . . . X-ray absorption coefficient determinations . . . shielding evaluation . . . isotope identification . . . Mesonic X-ray energy measurement . . . Na^{24} and K^{42} spectra with a human source . . . neutron time-of-flight studies . . . recording coincidences between protons and electrons in neutron decay . . . investigation of gamma-ray spectra involved in proton capture . . . two crystal Compton coincidence gamma-ray spectra experiments . . . three crystal pair production gamma-ray spectra studies" . . . ad infinitum.

* Actually, uses of the RCL 256 are as numerous and varied as our customers. The RCL 256 may be the solution to your radiation measurement problems. Call RCL or your nearest RCL representative collect. Their phone numbers are listed at the bottom of the page.

Improved RCL 256 Offers You These Advantages

Proven Reliability. The reliability of the RCL 256 is best attested to by its users. Over one-third of them now use more than one RCL 256. In fact, some laboratories use from four to ten RCL 256-Channel analyzers and consider them indispensable.

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Completely Integrated System. Scintillation high voltage supply and linear amplifier are built into the basic instrument.

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Detroit		Sao Paulo, Brazil	61-6133
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New Study Shows Nuclear Power May Be Practical and Economic for Merchant Ships

Some gray dawn in the early 1960's a heavily laden supertanker will shoulder her way through the steep Atlantic swells to a landfall in Delaware Bay. She'll be homeward bound for Philadelphia, 19 days out of Kuwait with nearly 40,000 tons of oil.

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No more dependent on thousands of tons of payload-stealing fuel oil, tomorrow's ships will range world-wide trade routes without refueling.

In the last twelve months she will have made eight trips to the Persian Gulf hand running. Now at last she is due for her annual refit... *and her annual refueling.*

Competitive at sea

A nuclear power plant for a ship of this type was the subject of a study recently completed by Atomics International for the Maritime Reactors Branch of the Atomic Energy Commission. Costs of building and operating a vessel powered by an Organic Moderated Reactor were compared with those for an oil-burning ship—a typical modern supertanker of some 38,000 deadweight tons.

Total costs for the OMR tanker, depreciated over 20 years, were only moderately higher than for today's conventional ship. But costs for oil-burners are on their way up, with steadily rising fuel prices seen from now on—whereas the cost trend for the OMR is downward, as nuclear technology is improved. An OMR tanker has greater cargo capacity because its fuel takes up little space. And it needs refueling less than once a year.

Bigger payloads, longer hauls, faster turn-arounds—this is the new pattern of operation. Shipowners can begin plans right now, for the Organic Moderated Reactor promises to put the atomic merchant ship on a sound commercial basis.

...ATOMIC ENGINES LIKE THIS

Al's Dr. A. B. Martin shows on this OMR tanker model how the compact power plant will free thousands of cubic feet of fuel space for revenue-producing cargo.

Versatile on land

The same features that make the OMR applicable for seagoing use are also in its favor for central power stations ashore. The basic simplicity and safety of this system point to economic nuclear electricity for many areas of the world today.

Plans are already underway to build an OMR plant in Piqua, Ohio, which will increase the city's electrical generating capacity by 12,500 kilowatts. Another OMR power station is planned for a Latin American country.

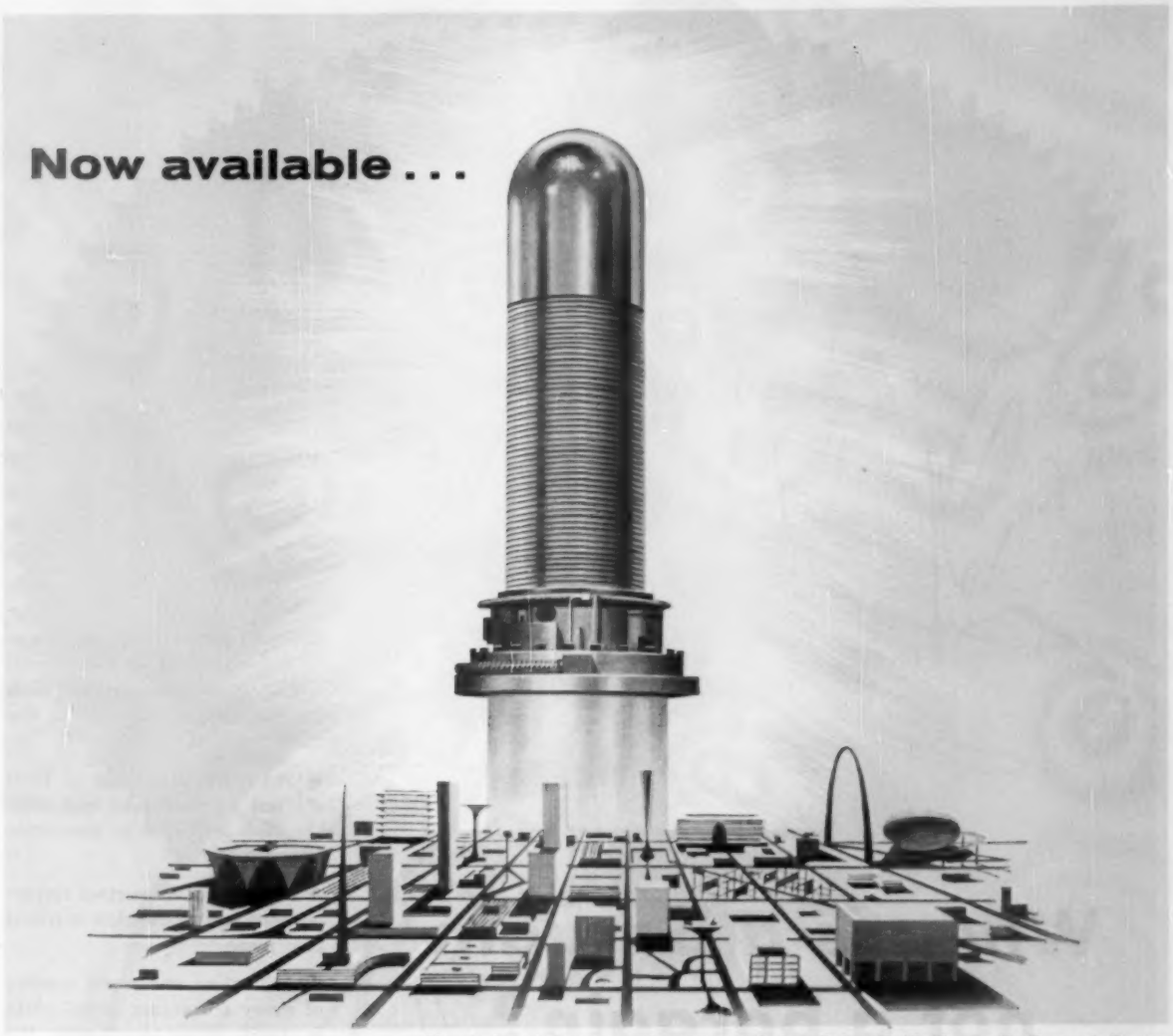
First OMR now in operation

All this stems from the results being achieved with the Organic Moderated Reactor Experiment, conducted by Atomics International for the Atomic Energy Commission. The Organic Moderated Reactor Experiment is being carried on at the AEC's National Reactor Testing Station in Idaho to establish the basic engineering data for this type plant. Atomics International is also operating the Sodium Reactor Experiment, a nuclear power project for the AEC. Another power reactor concept, the Advanced Epithermal Thorium Reactor, is under study for the Southwest Atomic Energy Associates. AI research reactors are now operating in Japan, Germany, Denmark, and the United States. Another is being built for Italy. ATOMICS INTERNATIONAL, P.O. Box 309, Canoga Park, Calif. Cable address: ATOMICS.

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

PIONEERS IN THE CREATIVE USE OF THE ATOM



Van de Graaff electron accelerator recently installed at Shell's Emeryville Research Center is one of the most powerful sources of radiation available to industry.

a radiation-resistant grease for commercial nuclear applications
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Nuclear applications bring new complexities to the field of industrial lubrication. Not only is the lubricant required to withstand unusual service with respect to temperature, speed, load and oxidation, but it is also exposed to the damaging effects of neutron and/or gamma or beta radiation.

To meet this challenge, Shell Research has developed a practical radiation-resistant grease for use in nuclear reactors and their component parts . . . Shell APL Grease.

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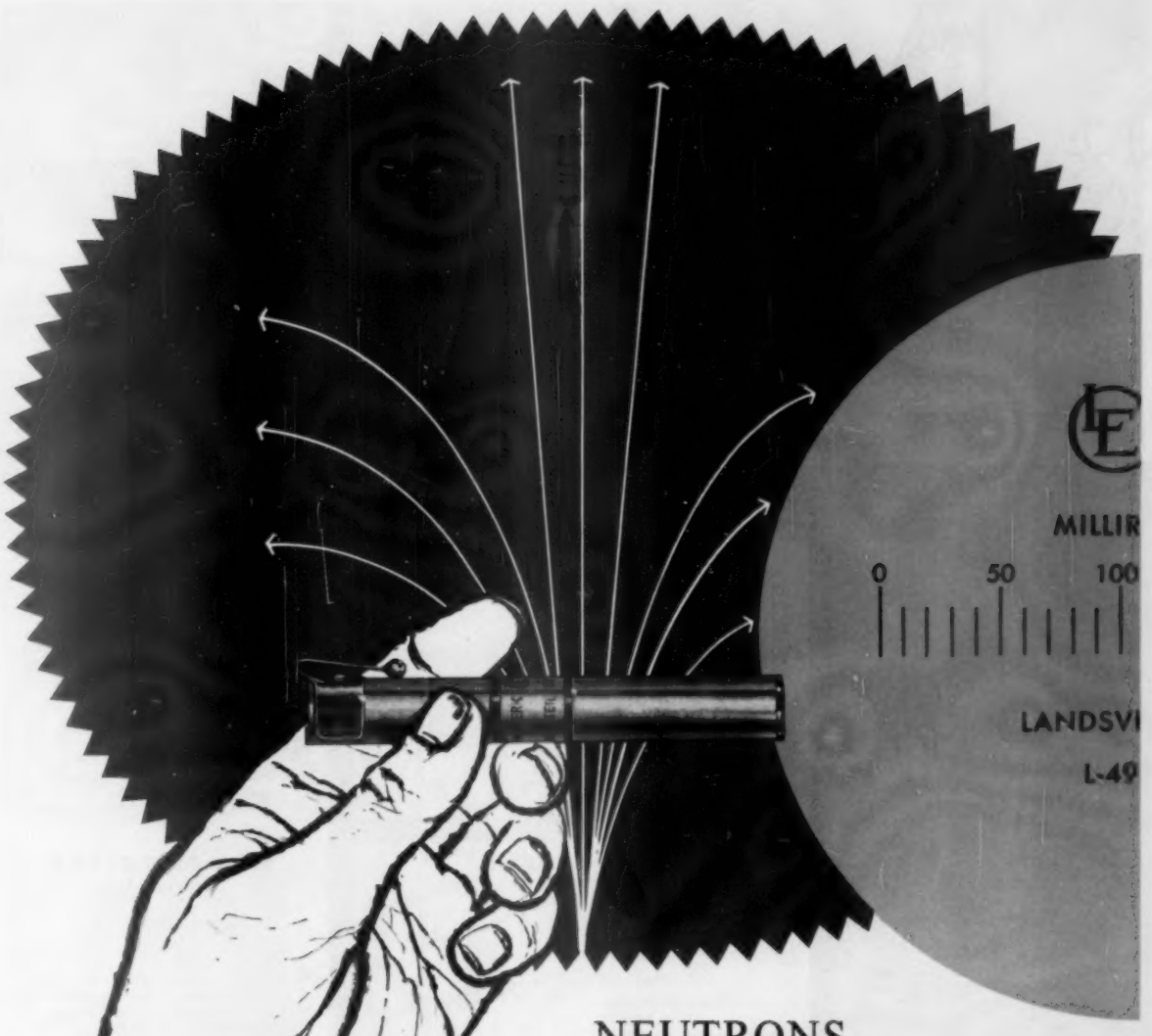

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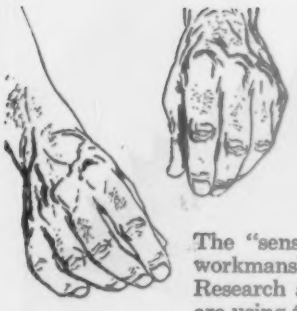

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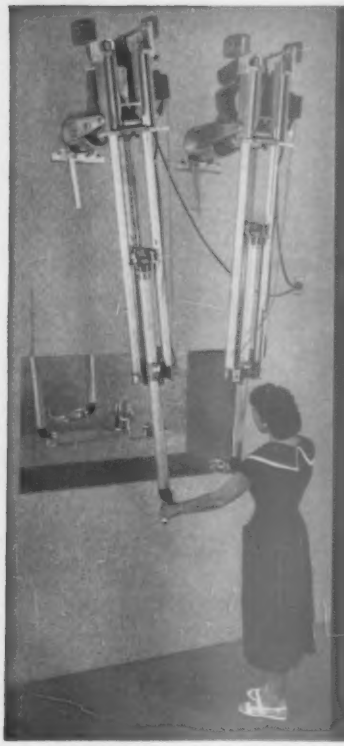

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A general purpose manipulator for installation over a barrier wall or through a ceiling opening of a protective enclosure.

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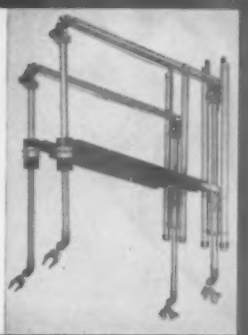
A space conserving, light weight manipulator for use in hoods or over thin walls where minimum clearances and easy portability are important factors.



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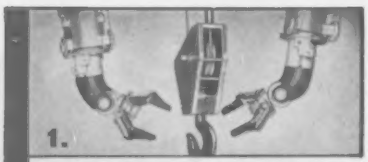
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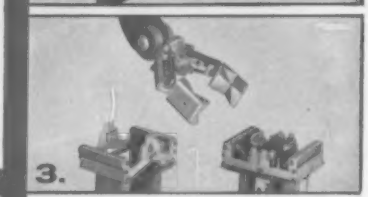
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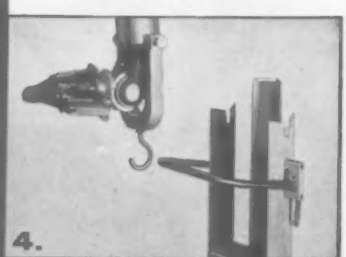
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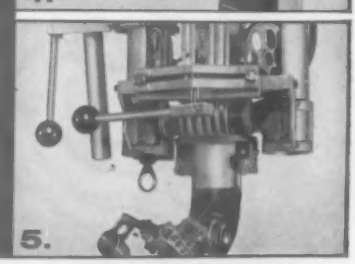
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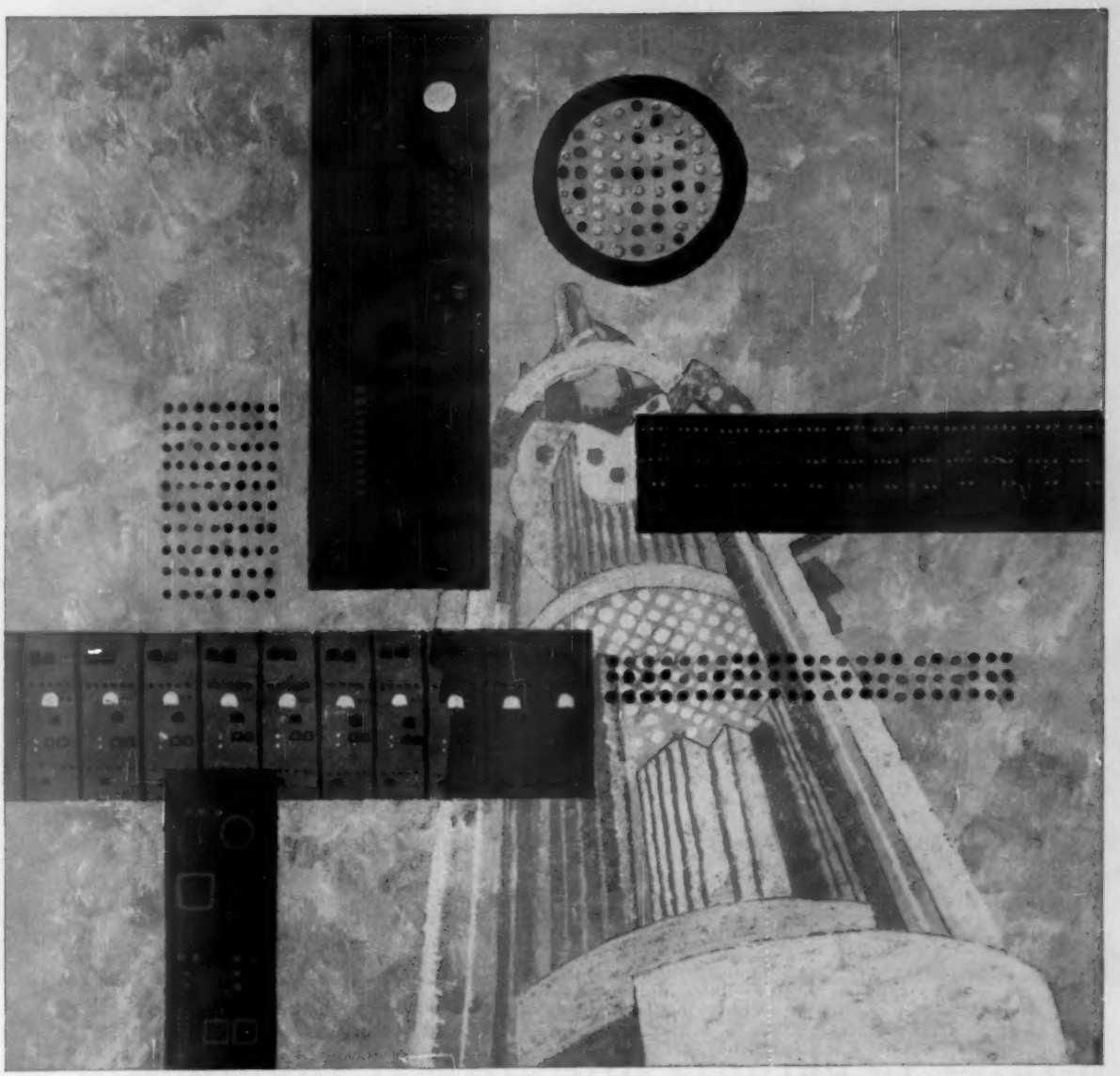

Nuclear Instrumentation and Control Systems for Power Reactors, Test Reactors, Marine Propulsion

from a decade of nuclear pioneering . . .

Instrumentation for Every Atomic Need

Plowback of Earnings into research, development and engineering has been an established policy at Westinghouse since its founding. This research program led to the development, over 10 years ago, of extensive atomic studies to find the most practical techniques for harnessing nuclear power. The experience gained in early atomic programs has made this field an established *industry* at Westinghouse.

Coupled with this research leadership, years of engineering, design and manufacturing know-how enable Westinghouse to produce the only *complete line* of nuclear control and instrumentation equipment.

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Openings at all experience levels

ANALYZE	Degree essential. Experience as required. **Preliminary analysis:** Conduct preliminary analysis and design of overall power reactor systems and components. **Shielding analysis:** Advanced studies and analysis on stationary and mobile plants. **Systems analysis:** Engineering direction on reactor plant design. **Control analysis:** Reactor kinetic and overall nuclear power plant control. Hazard analysis. Analog and digital computers. **Core analysis:** Includes criticality, temperature, void and power coefficients, control effectiveness and fuel cycles. **Stress analysis:** Structural, thermal, and dynamic stress analysis of high temperature reactor systems. **Heat transfer analysis:** Reactor systems—dynamics and thermo-dynamics of fluid flow. **Operations:** Foreign and domestic—for checkout, start-up and training.
DEVELOP	Requires related experience and applicable degree. **Instrumentation and control:** Physicists and EE's for design and development of advanced design vacuum tube, transistor, and/or magnetic amplifier control and instrumentation components. Design and analysis on reactor control systems, using stability and transient response techniques. **Fuel elements:** Metallurgists for R&D on nuclear fuel materials, including radiation effects, evaluation of uranium and thorium alloy, and ceramics. Also for mechanical fabrication development for these materials. **Nuclear fuel reprocessing:** Inorganic and physical chemists for developmental studies and experimental work. Experience with radio-active materials and high temperature processes desirable.
DESIGN	Senior openings. Degree required. Nuclear experience preferred but not essential. **Control mechanisms:** Control and safety rods, drives and allied tooling. **Reactor core components:** Moderator cans, fuel elements, core supporting structures. **Machine design:** Heavy mechanical. **Electrical:** Reactor control and power systems. **Process systems and equipment:** Pumps, Heat transfer equipment. **Facilities:** Mechanical systems. **Process instrumentation:** Reactor, auxiliary, and control systems.

Other opportunities in:
Theoretical, Experimental, Solid State Physics, Health Physics, Materials Research, Mechanical Component Development.

New programs add to years-ahead backlog

Atomics International has built and is operating two power reactors—the Sodium Reactor Experiment and the Organic Moderated Reactor Experiment. Central station power plants based on these reactor concepts are in the planning stages right now. In addition, AI has just begun an advanced power reactor study for Southwest Atomic Energy Associates, a group of 15 investor-owned utility companies.

AI is expanding overseas operations. With 5 foreign reactors already in operation or being built, AI recently signed agreements with ASEA of Sweden, which has offices in 50 countries, and DEMAG of West Germany, with whom AI formed the new company, INTERATOM, in Duisburg, West Germany.

Write today for more details about exciting career opportunities at AI.

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15330 Raymer Street, Van Nuys, California
(In the suburban San Fernando Valley, near Los Angeles)

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Fuel-element irradiation studies at 1700°F

Irradiation studies of experimental fuel elements at high temperatures (1700°F) for a projected gas-cooled reactor design are now being carried out by Ford Instrument Co. engineers at the reactor facilities of Brookhaven National Laboratory.

Major aims of the fuel-element irradiation programs are to study fission product diffusion and leakage, and to secure radiation damage information. The studies are directed toward development of a fuel element that can be fabricated economically with a low reject rate, that uses material of low enrichment, that can be reprocessed economically and be economical of fuel inventory.

Irradiation of fuel elements at high temperature is just one of the nuclear studies and projects completed or now under way by Ford Instrument. Others include: design of a complete closed-cycle gas-cooled reactor, manufacture of control rod drive mechanisms (e.g., as used in the submarine, *Seawolf*), control rod position indicators, magnetic and transistor amplifiers for nuclear applications, and studies of control rod and reactor materials. In addition, Ford Instrument is conducting numerous feasibility and experimental studies in the nuclear field, including the application of digital techniques to reactor control.

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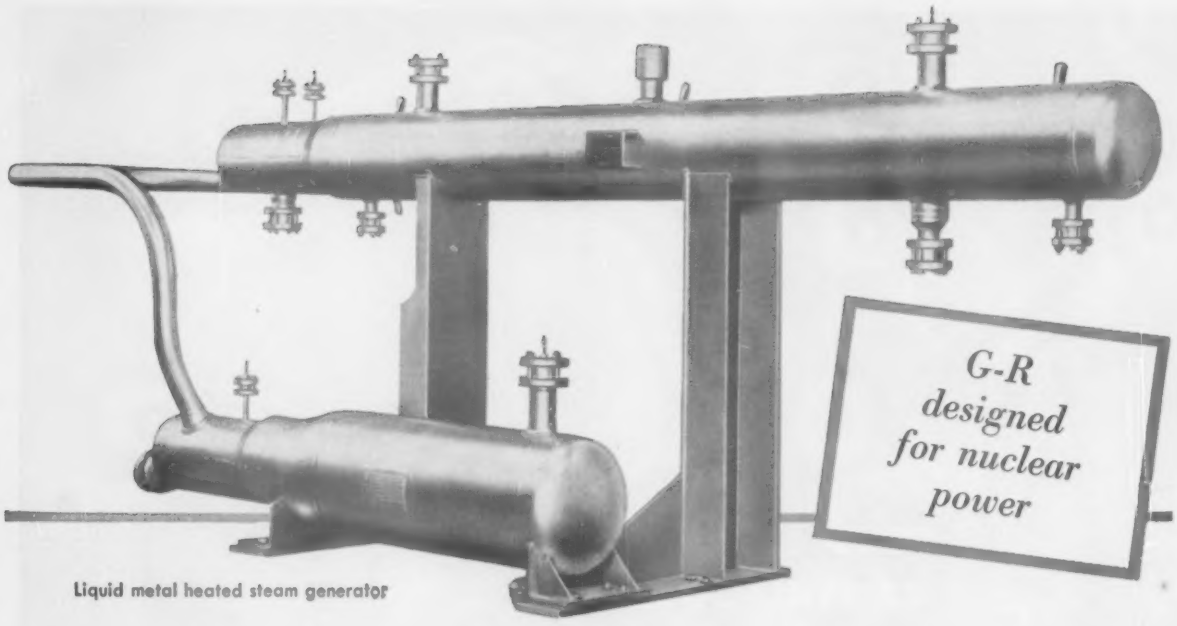

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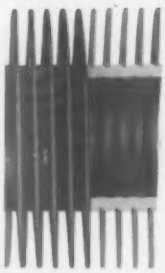

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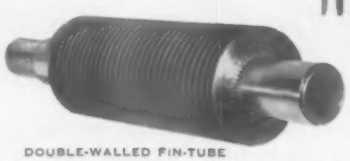

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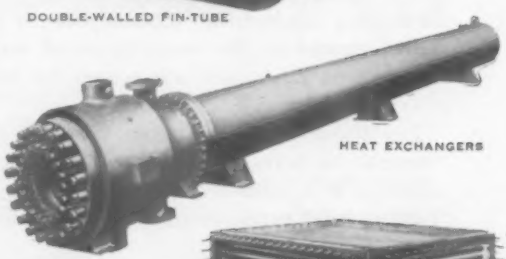

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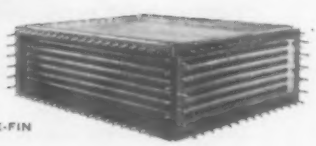

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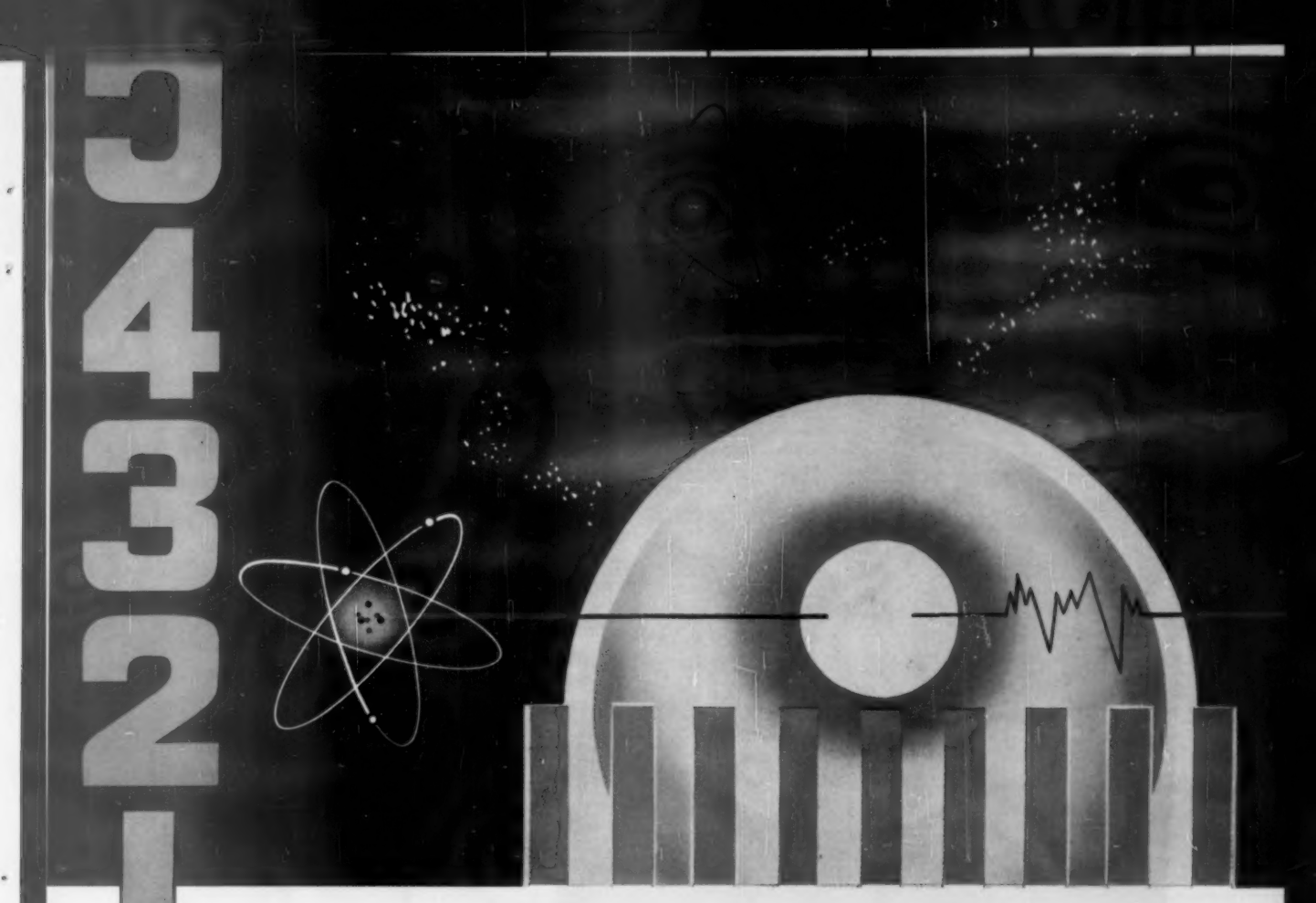

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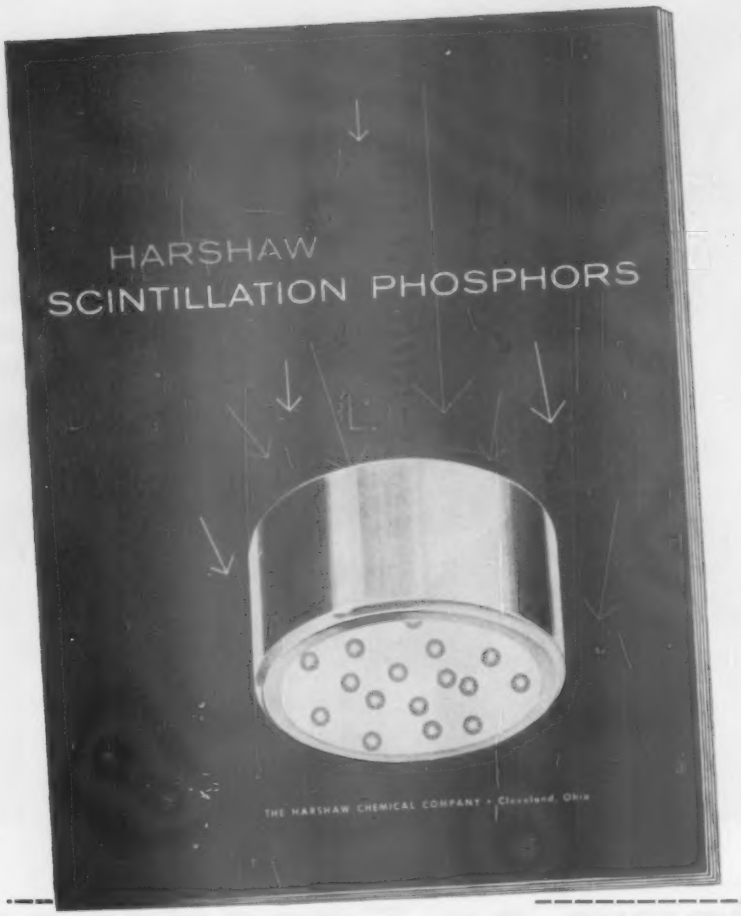

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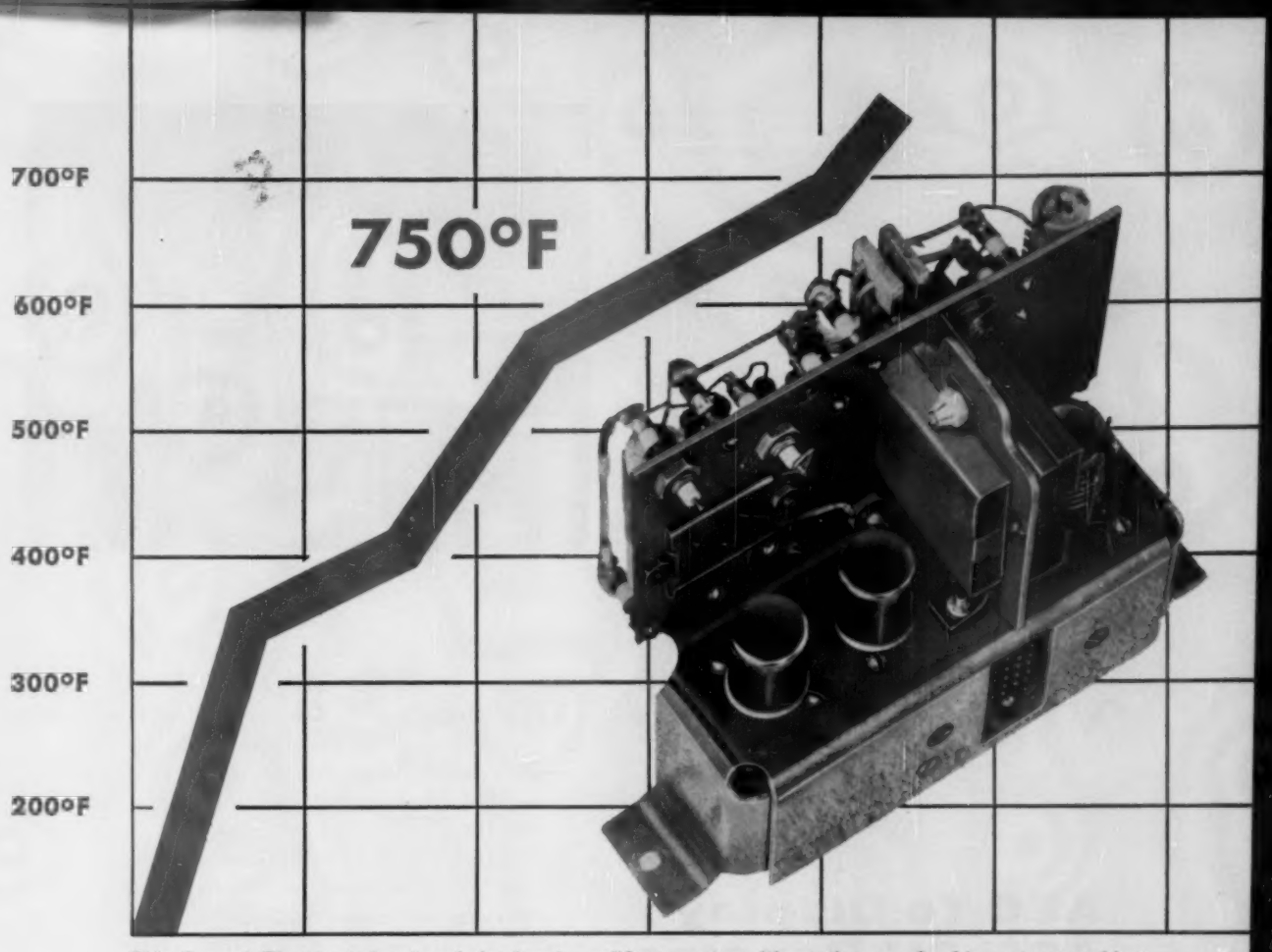

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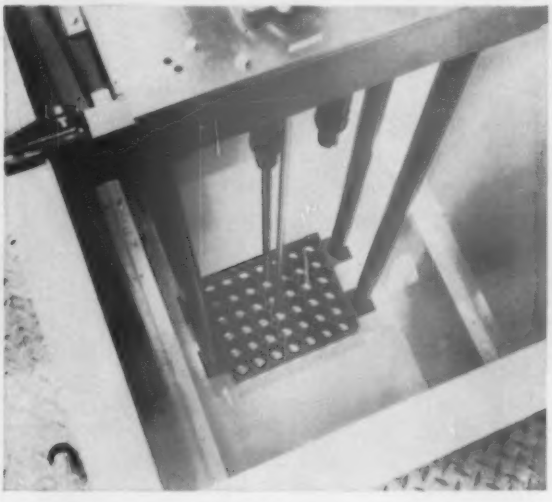
Grid support assembly of the Brussels AGN-211 reactor, shown during construction.



AEC To Display AGN 211 Reactor In Brussels Fair

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Fuel elements of the AGN-211 reactor being assembled for Brussels Fair. Note similarity to building block construction.

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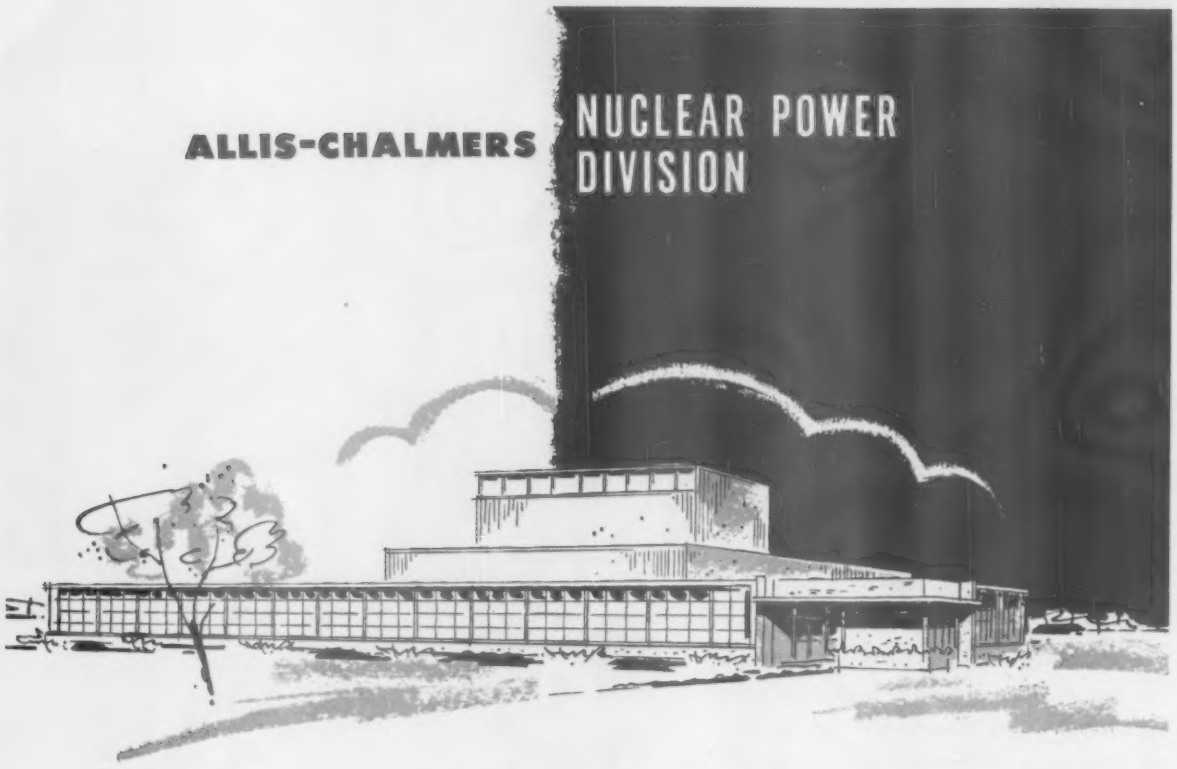

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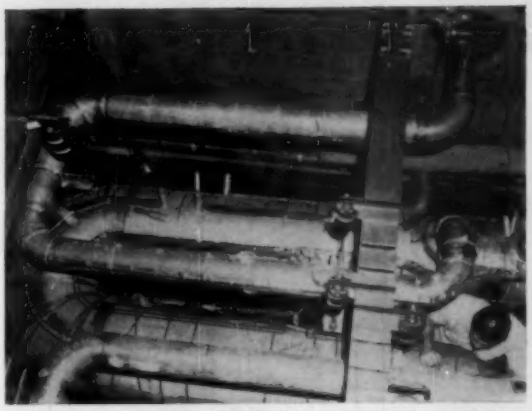

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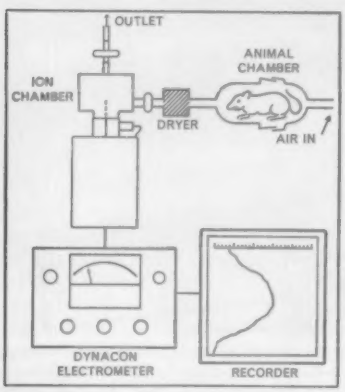

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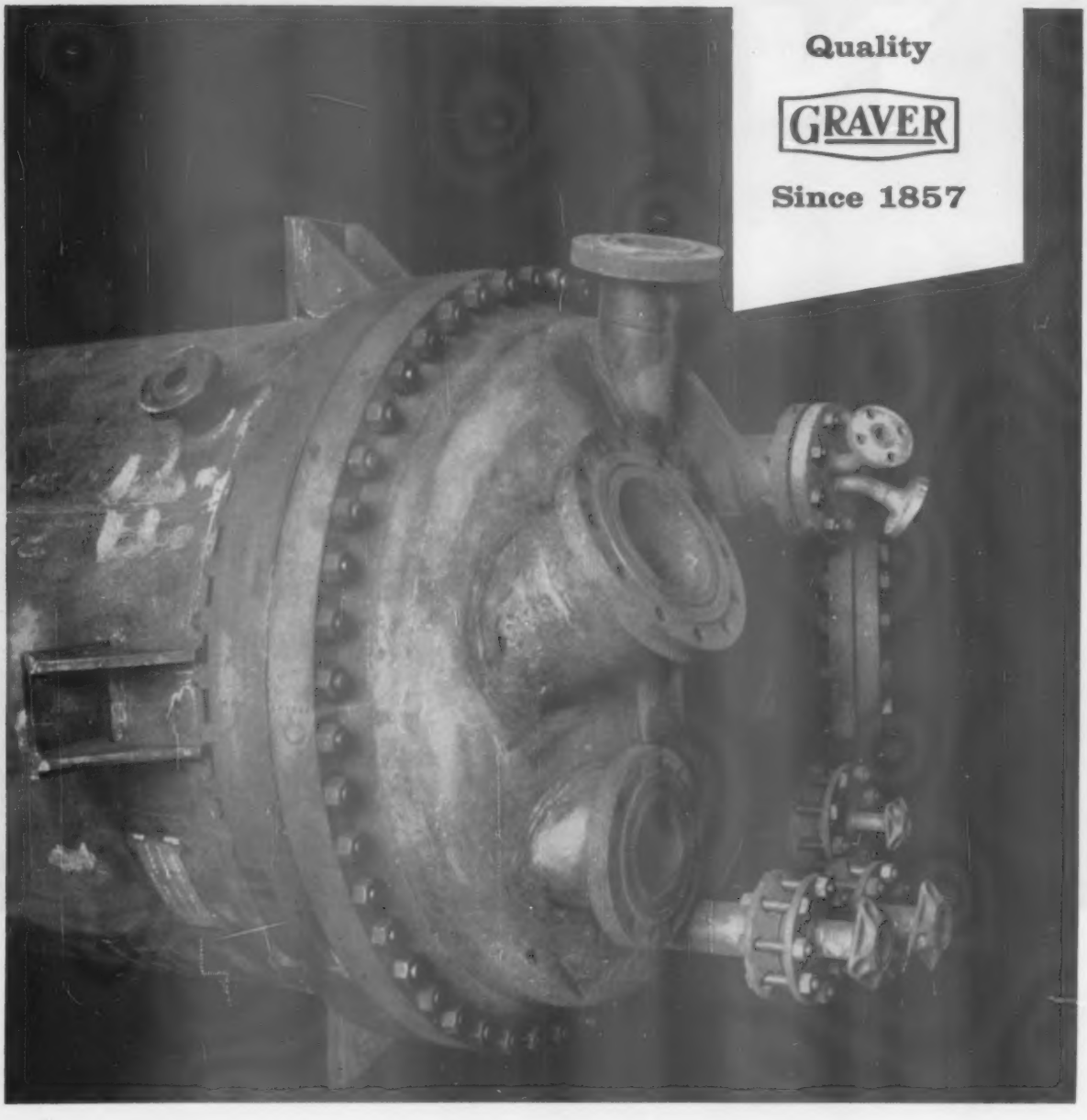

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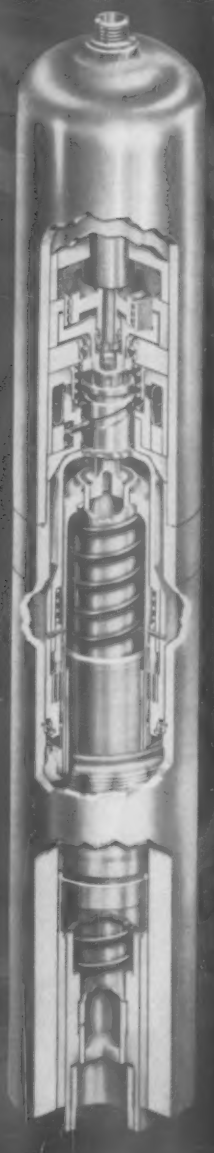

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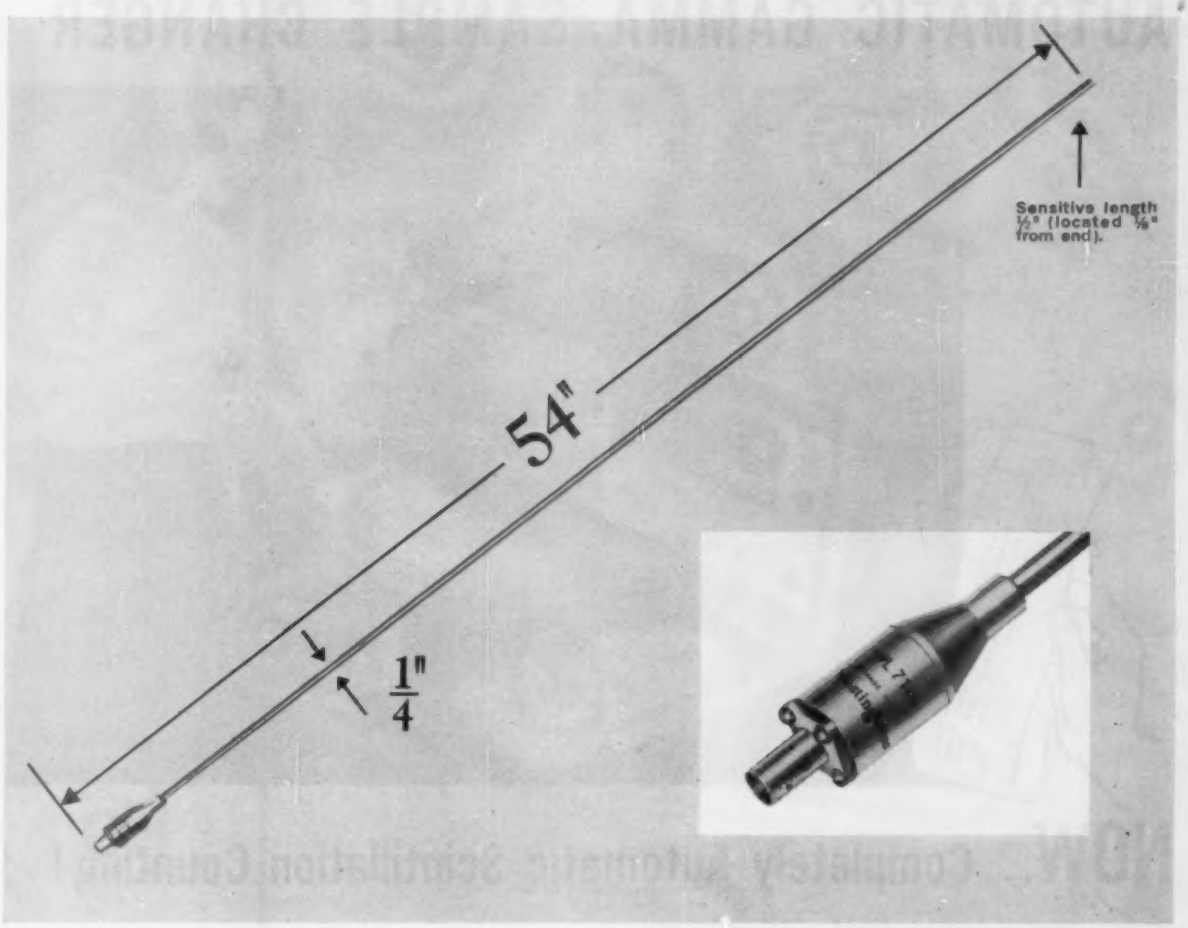

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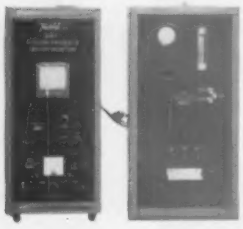

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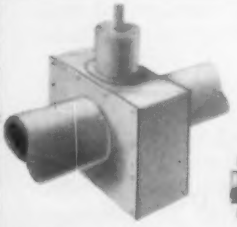
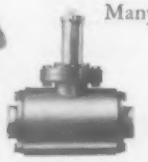


Beta and Gamma



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A NUCLEONICS Special Report

Power Reactor Control

Without reactor control there could be no power reactors. On it falls heavy responsibility for safety, reliability, efficiency and economy of nuclear power plants.

But reactor control is in transition, reacting in a sensitive manner to advances in reactor design and changes in safety philosophy. Therefore, this report has been designed to show both today's power-reactor control and the direction of its development. We asked our authors to stress those aspects that are new or undergoing rapid development. The subjects covered include design philosophies, control problems and their solutions, control rods and their drives and special safety devices. Articles on spectral-shift (p. 80) and chemical (p. 82) control provide a sample of the novel methods that may play a part in the control of future reactors.

To determine the present status of power-reactor control NUCLEONICS directed a questionnaire to the designers of most of the world's power reactors. The responses, contained in the discussion and tables of pages 71–77, provide for the first time an over-all view of where we stand in the practice of reactor control.

Thus our story is—power reactor control, today and in the future.

—The Editors

TYPICAL REACTOR CONTROL SYSTEM has three interconnected loops for startup, operation and shutdown. Philosophy of control determines how the loops accomplish their purposes

FIG. 1 ➡

Reactor Control Philosophies

Different reactor types demand different approaches to control problems. From many available philosophies, designers must find one that assures safety in startup and shutdown, economy and efficiency in operation

By M. A. SCHULTZ, *Westinghouse Electric Corp., Pittsburgh, Pennsylvania*

NUCLEAR-POWER-PLANT control philosophy in this country is primarily concerned with over-all safety. The science has not yet progressed to the point at which efficiency and economics can be introduced as prime factors. Consequently, in a climate of preoccupation with safety, the control-system designer quickly finds himself enmeshed in problems of basic reactor-design philosophy.

Choice of Reactor

The first problem to be resolved is what type of reactor shall be built. This question is usually answered on an economic, political or other basis, but there is also a distinct control-philosophy question involved.

The argument develops as follows: The processes involved in a reactor are dangerous and, consequently, some control is needed to operate safely. A power reactor produces heat. Moreover the heat must be produced in a slow and steady manner to be useful.

We can consider here two types of reactors—inherently stable and inherently unstable.

External Control

One reactor-design school, first championed by Canadian designers, feels that nuclear power plants should follow the pattern of simple reactors with complex external control. Its argument is, "Reactor economics are admittedly poor. The designer has a tough enough problem in attempting to design a cheap, economical reactor without the added restriction that the reactor must protect itself. Call on the control engineer to protect the reactor by means of external devices.

"Positive temperature coefficients should be permitted and any economic grouping of materials should be allowed. Circuitry is now available to ensure complete protection."

This philosophy usually calls for a large number of scrams or shutdown circuits in the control system. Some reactors have hundreds of scram circuits.

Internal Control

The alternative philosophy starts by restricting reactor design to a stable configuration. This is currently used in the United States and Britain. Many possible reactor types probably will not be permitted despite the apparent present desire to try every approach in this country. This philosophy means a moderate-to-large negative temperature or void coefficient for the reactor and a restriction to compatible materials.

The question is, "Does restricting the reactor design to one that can protect itself necessarily mean a more expensive core and plant?"

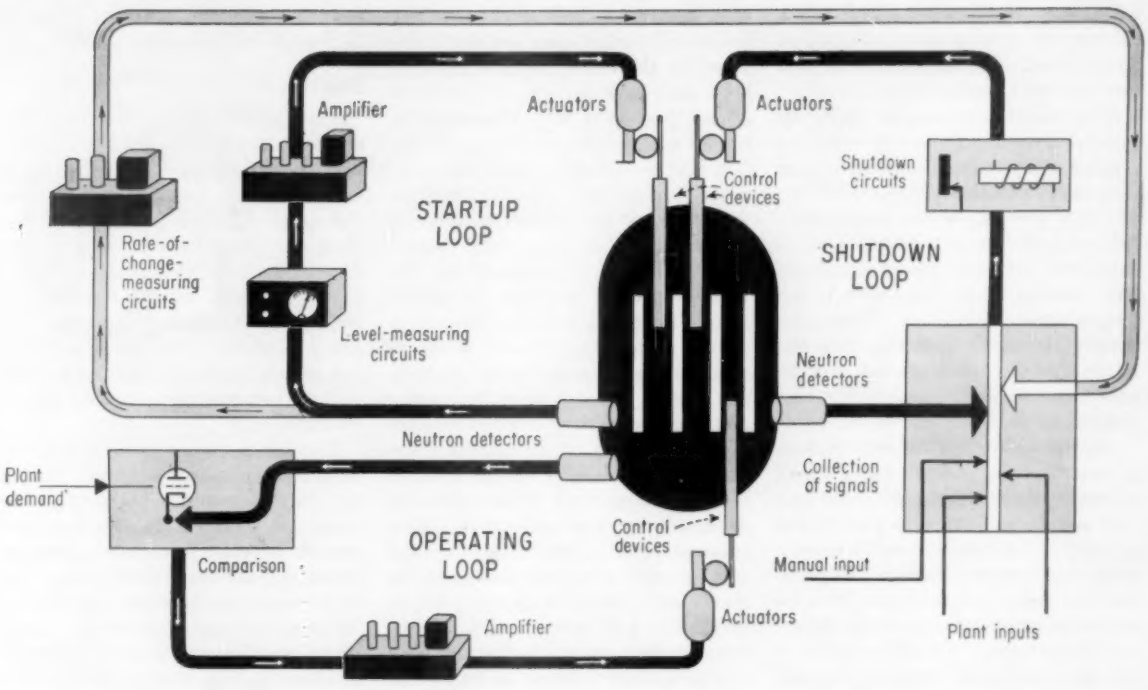
It has been shown that for some reactor types, such as pressurized-water or boiling-water, the safety provided by a large negative coefficient is essentially free. Changes to alter the temperature coefficient to an optimum value can be made by comparatively slight material proportion changes in the fuel-to-moderator ratio.

Some reactors can be made to protect themselves simply and cheaply against most accidents. Other conceivable accidents may then require a minimum of external circuitry, possibly only one or two scram circuits. Therefore, there appear to be reactor designs and configurations that offer economic performance, along with low-cost built-in internal protection. However, the freedom of design provided by sophisticated external control systems is most appealing.

Cost Factors

Once the reactor type is chosen, more detailed concern can be given to the cost of the safety control system. From the viewpoint of the reactor builder, the principal ingredients of plant safety are:

1. Protection of the plant by proper design of reliable instrumentation and control systems—not necessarily by



multiple instruments or over-control.

2. Protection of the general public after an accident by containment.

In most power reactors in this country, containment appears to be a necessity. Sufficient experience is not yet available in power-reactor operation to consider abandoning containment in complete favor of better instrumentation design. A few voices have arisen that this approach should now be considered and a reasonable risk taken (NU, Jan. '58, p. 71), but clearly more experience with operation is needed.

Now if it is granted that a foreseeable accident creates a statistically intolerable situation to the surrounding neighborhood, no major reduction in reactor safety costs can presently be made. The cost of the containment system far outweighs the dollar value of any economic argument on detailed control-system philosophy.

Control Approaches

We can now look at choices available in working out the basic control system. It is assumed that reactor type has been selected, its nuclear characteristics are known, and the transfer function giving performance as a control component has been determined. External-control design is then started. Figure 1 is a representation of the problem in block-diagram form showing the system as three interconnected loops—startup, operating and shutdown loops. These networks clearly have the reactor as a common component and can have other external interconnections.

Each block of Fig. 1 requires a philosophic choice in its conception. Presumably most of these choices can now be made on a technical or economic basis.

Startup

In the startup loop the choice must immediately be made as to whether this loop shall be manual or automatic in the blocks marked "amplifier" and "actuators." Automatic startup of a reactor is completely feasible on a technical basis and some reactors are already using automatic or semiautomatic startup.

The problem can be resolved on an economic basis, and operating costs and local labor conditions will probably prevail in the decision. For example, a power reactor used in a submarine probably has no great need of automatic startup in that there is a ready supply of labor available for reactor operation at no extra cost. On the other hand, in a complex electrical generating plant in a large city with an expensive labor market, considerable automation can be written off against operating costs.

Nuclear instrumentation. The next choice is how much instrumentation in the block designated "neutron detectors" must be provided. In early power-reactor designs excess nuclear instrumentation was furnished for extreme safety. It was felt that nuclear instrumentation, being new, would not be very reliable, and to provide a reactor plant with just one channel of neutron information would be foolhardy.

This argument very quickly raised the argument against using two channels: With the same poor instrumentation the question arose as to which channel should be believed. Consequently, three-channel instrumentation was installed in several plants, and if any two channels read alike, these are presumed to be correct.

Nuclear instrumentation has proved to be as reliable as any other type and perhaps even more so because of the great emphasis and care taken in its design. However, other subterfuges are now being used to retain multiple-channel instrumentation. For example, the theory of wired spares has been evolved around the argument that no one would operate a nuclear reactor without spare instruments; and as long as these instruments are on

hand, they can as well be stored in a cabinet; and as long as they are stored in a cabinet, they might just as well be wired up in operating channels.

The true situation is that the safety picture dominates and forces the present use of parallel nuclear instrumentation. Despite present reliability of this apparatus, a minimum of two independent channels appears indicated for each function. Coincidence and auctioneering type circuits no longer appear necessary. Two independent channels, however, have the advantage that each channel can be checked separately even while the plant is on the line.

Control speed. The next problem is how fast the control devices shall operate. Here again performance as well as safety dictates the answer, but the decision can be made on a reasonably good technical basis. The problem of xenon override and burnout results in one minimum required control-device speed. Reactor startups are also limited by temperature and stress considerations and, for military plants, tactics. Each reactor has its own problems, which call for both a minimum and a maximum required reactivity-change rate, but quite clearly safe startup systems can be designed using reactivity change rates ranging from 10^{-1} Δk/sec to 10^{-5} Δk/sec. Safety suggests the slower speeds.

Operating Loop

The problems of the operating loop are accuracy as well as reliability of output. Generators of electricity are required ultimately to supply the user with a fixed voltage at a constant frequency. What then are the limits to which the reactor output must be held, and how reliable is this new source of power to be? The consumer is not the slightest bit interested in the fact that a reactor has shut down because of a bad tube in a servo amplifier when he plugs his toaster into the wall socket. Consequently, the present trend is for operating loops to have no vacuum tubes in key roles. Magnetic amplifiers or transistors replace them.

The manual-automatic problem comes up again in the operating loop, and here it is more likely that automatic control will be selected because of the frequency of adjustment. Assuming an automatic system, a choice is available between proportional and discontinuous or on-off control. Proportional systems are capable of somewhat greater accuracy, but as either type can regulate the power level to better than 1%, there is little to choose from on this basis. A discontinuous system is simpler and not as susceptible to noise. Also the dead zone of discontinuous control makes control-rod positioning somewhat easier in that magnetic brakes, gearing, and other forms of friction can be used.

Control devices. The actual control device usually takes the form of a regulator rod or a regulating form of leakage or poison that has little reactivity worth. General practice is to limit the reactivity of the regulating device to a value less than that required to go prompt critical. However, in reactors where control rods are combinations of shim, safety and regulator rods, this criterion need not be firm if the rods move slowly.

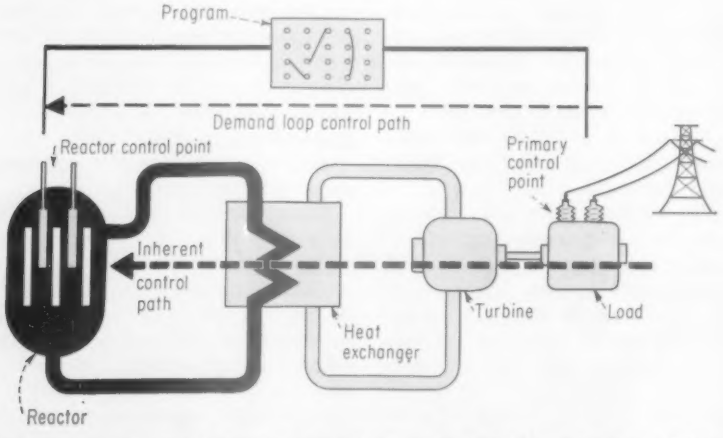


FIG. 2. Simplest control (bottom) uses only feedback inherent in reactor system. External program (top) feeds load-demand signal back to reactor control point so that reactor will anticipate needs of rest of plant

Shutdown

The shutdown loop differs from the others in that it normally is not working. It is used only during an accident or malfunction and provides signals to turn off the reactor by either scramming or cutting back on power level. As previously indicated, the number of signals injected into the shutdown loop is a function of reactor design philosophy. The entire basis for scramming, however, may well need to be re-examined for future power reactors.

The scram circuit itself is a somewhat new industrial concept. Safety devices that turn something off in the event of overheating are common enough in industry but differ from the scram in two important respects—speed and many-decade shutdown. The type of shutdown generally means continuing instrumentation following a scram and also a large delay before the reactor can go back on line.

Over-power scram. At present, reactors employ for protection what is commonly known as an over-power scram. If the power out of the reactor exceeds normal rating by a given amount, the reactor will be caused to scram. The over-power trip point for power reactors can vary from 110% to 200% of full power. This use of a scram is proper as long as reactors are isolated, uncommon devices.

However, there are both immediate and longer-range problems in the indiscriminate use of this scram. It is granted that in the next decade, power reactors will be only a very small part of many utility networks. The loss of any one electrical generator probably will not affect the network as it undoubtedly will supply only a small part of the load. Hence the over-power scram and any other supersafe device can be indulged in to the limit of economic feasibility.

As more and more electrical power is generated from nuclear energy, power systems will not continue to find complete scrams tolerable. It appears that a nuclear power plant will be cheaper on a dollar-per-kw basis the larger the plant. Nuclear plants of 1,000-Mw electrical output are not beyond present-day conception. If one of these plants were removed from the line by a scram, a larger ripple

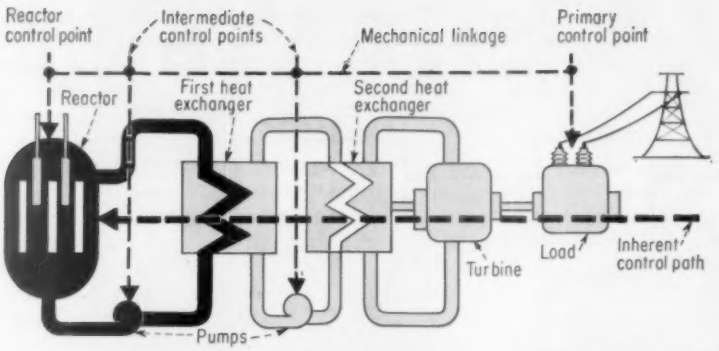


FIG. 3. Parallel control sends simultaneous signals to several different control points through the system for improved over-all response

might occur on the system with resulting damage and protest.

To carry the situation to an extreme, imagine a complete electrical system supplied from a few nuclear-powered generators with controls operated in accordance with today's scramming philosophy. If one reactor were to receive a transient surge to 30% above its rating, for example, regardless of how short the duration of this surge, this plant might scram off the line. This effect immediately presses heavier demand requirements on all of the other reactors of the system, and if they attempt to meet this demand with closely set scram levels, it is quite conceivable that the entire system might be caused to scram out.

Such operation would, of course, be intolerable. Overload control of a different type surely will have to be provided for tomorrow's reactors operating in utility systems.

Reason for over-power scram. Why should a present-day power reactor have an over-power scram? The answer quickly boils down to separate considerations of energy-handling capacity on both steady-state and transient bases. First, for the steady-state condition, let us assume that we have a reactor that has an output capability very close to its rating. That is, the reactor may be capable of putting out continuously only 1.1 times its rating.

It appears that in normal steady-state operation, if the power level drifts or otherwise changes slowly in this reactor from 100% to close to 110% of its rating, a violent scram is not justified. Some milder action would be sufficient.

Most suggested accidents can be analyzed in terms of a change of reactor power level. Transients originating at the load end of the plant usually fall into the slow-drift category in that many seconds are available to do something about them. This effect, coupled with the fact that a properly built-in negative temperature coefficient also mollifies the accident, effectively eliminates the need of a scram to protect against power-level changes originating in the load.

Fast transients. It now appears that the only transients that need be considered for scramming protection are the fast ones that originate in or near the reactor. First, the reactor clearly has a transient rating different from the steady-state rating depending on the shape of the transient and the reactor heat capacity.

A good example of a reactor-originating transient is the startup accident. Here it is conceivable that any type of reactor can get on to a fractional-second period. An over-power scram set modestly high, say at 150–175% of full-power rating, does about as much good as one set lower in that the integrated output energy under a pulse having both a steep front and a steep rear edge is likely to be small. A low-set scram would have only nuisance value for steady-state drift and slow transients.

This situation of course must be examined for each individual reactor on a heat-capacity basis, but clearly the condition previously described of a utility system scramming off the line can be avoided by using a high-set scram to catch fast transients that originate near the reactor. Transients originating in the load can be taken care of in some other manner.

Plant-Control Philosophy

It is a well-established principle of control systems that the primary control point should be as close to the output or working part of the system as possible. In the case of a nuclear power plant this means that the primary control should start at the load end of the system rather than at the reactor. The bottom portion of Fig. 2 illustrates this situation. We can consider the control paths that are involved starting from the output and working back to the reactor. In a reactor having a negative temperature coefficient, it has been demonstrated that the load reflects back directly into the reactor so that any change in load creates a corresponding change in reactor output. In Fig. 2, in the absence of an external control path, more load calls for lower temperature into the reactor and hence more reactivity via the negative temperature coefficient. The control path is essentially through the system itself. The reactor can be operated independently from a reactor control point to handle such problems as startup, xenon, or depletion, but essentially the steady-state minute-by-minute load demands are taken care of by the control path through the system.

Demand loop. As there are usually variables other than power output involved, additional control paths may be required. Figure 2 indicates the addition of a demand loop to the basic plant. Here two control paths permit regulation of another variable such as temperature or pressure as well as maintaining the desired power output. The time constants of these two paths generally are made widely different for stable control operation with the control path through the system usually faster and the demand loop slower.

Parallel control. Some types of plants have large amounts of piping or long time delays in the basic control path through the system. This may require parallel rather than the series control just illustrated. Figure 3 indicates such a situation for a reactor plant with two heat exchangers. In the control indicated the change at the primary control point is also made immediately at several intermediate control points. Local minor loops around each major component are sometimes required to settle out the system around programmed variables.

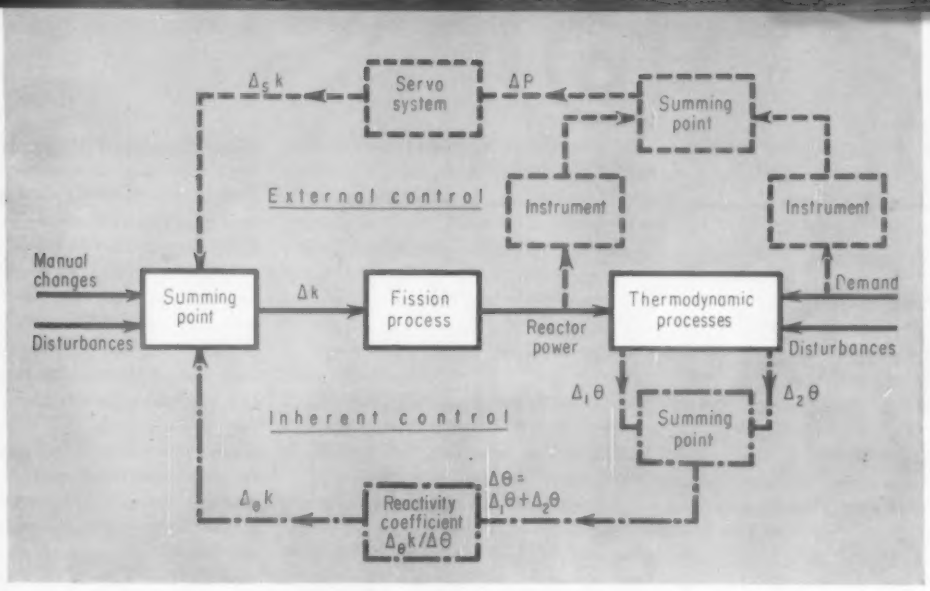


FIG. 1. Reactor response is determined by combination of external and inherent feedbacks. $\Delta_1\theta$ and $\Delta_2\theta$ are changes in some variable caused by changes in reactor power and load demand, respectively. Result is $\Delta_e k$. ΔP is difference between power and demand, and result is $\Delta_e k$

Today's Control Design

Inherent and external feedback are the control designer's tools in solving four important problems of reactor behavior—startup, stability, transient response and programming

By JOHN MacPHEE, *Consulting Engineer, Rowayton, Connecticut**

REACTOR-CONTROL analysis is concerned with feedback systems. The designer must evaluate various inherent feedbacks and if necessary add external control loops. It is his responsibility to use both internal and external control to make the reactor as safe, economical and efficient as possible.

No single approach can be shown to be ideal at this time. Each reactor type has its individual characteristics. Moreover, even after the type has been selected, there are various ways to program plant variables in the attempt to match reactor performance and load.

Control Requirements

For control considerations a reactor system can be represented schematically as in Fig. 1. The input to the fission process is the sum of changes in reactivity produced by external disturbances such as noise and changes in control-rod position made by operator or control system. In addition there are inherent reactivity changes produced by feedback due to temperature and density variations. The output is power, which is removed by one or more thermodynamic processes. These processes are also subject to disturbances such as loss of coolant flow and inadvertent opening of valves.

The variables $\Delta\theta$ in Fig. 1 represent changes in any of the many variables which describe the state of the system —temperature, pressure, density, etc. $\Delta_1\theta$ represents the change in θ produced by a change in reactor power, while $\Delta_2\theta$ represents the change produced by a change in demand. If there is a reactivity coefficient by which a change in θ produces a change in reactivity of the correct sign, we can make use of it and have an inherent control system.

External control. If an external control system is required, it can be designed to serve as an artificial reactivity coefficient, as shown in Fig. 1. Instrumentation is used to measure reactor power output and demand, the difference ΔP being applied to a servo system that moves a control rod. ΔP is analogous to $\Delta\theta$ and the servo system is analogous to a reactivity coefficient.

The reactor system must meet four basic problems:

1. Startup. This phase of reactor operation can be hazardous. At low

* PRESENT ADDRESS: AMF Atomics, Greenwich Conn.

power inherent feedback is relatively ineffective and cannot be counted on to shut down the reactor until an appreciable power level has been attained. Therefore it is possible to get the reactor on a very short period by the time a significant power level is reached. This, of course, suggests using automatic startup.

2. Stability. The system must be stable, which means that sustained oscillations must not occur. Stability is strongly dependent on the magnitude of the over-all reactivity coefficient. A system with a large coefficient tends to be more unstable. Thus in a boiling reactor this is a real problem.

3. Transient response. The reactor must be able to accommodate changes in many of the variables. These changes can be classified as long-term and short-term, or sudden. Long-term changes include fuel burnup and xenon buildup. Short-term changes are those of shorter period.

In some systems inherent feedback provides adequate transient response. In others additional control equipment must be added.

4. Steady-state programming. This refers to the manner in which steady-state values of the variables that describe the state of the reactor system change with the level of the reactor power. These variables include coolant temperature, coolant pressure, average coolant density and the turbine-fluid properties.

Startup Procedure

Borax and SPERT experiments have demonstrated that short periods in startup are not necessarily catastrophic, but the self-shutdown mechanism involved is not well enough understood to allow extrapolation to different design conditions. Therefore it has generally been the practice to design startup systems so that no credit is taken for a self-shutdown mechanism.

Consequently the maximum rate at which reactivity can be added is usually established on a very conservative basis. As a consequence of this the only advantage automatic startup offers is to give operating personnel a reduced program of duties during startup. It is not surprising then that most power reactors have manual startup. An exception is NRU (*1*).

The use of U^{233} or Pu^{239} as a fuel can have an effect on the startup system,

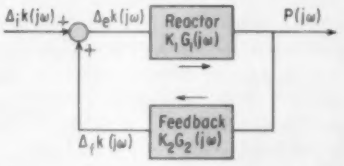


FIG. 3. Frequency-response method describes system in terms of steady-state sinusoidal response $P(j\omega)$ to sinusoidal driving function $\Delta_i k(j\omega)$. K's are gain constants, G's are frequency-dependent responses usually normalized to unity at $\omega = 0$. Open-loop response is $K_1G_1K_2G_2$. Closed-loop response is $P(j\omega)/\Delta_i k(j\omega)$

depending on its design. This is because of the reduced fractions of delayed neutrons these fuels have, as shown in the table on page 68. The effect of reduced values of β on the steady period is shown by Fig. 2 for a prompt-neutron lifetime of 5×10^{-5} sec. Thus if the design of the startup system for a given reactor fueled with U^{235} assumes that the reactor never becomes prompt critical, the use of Pu^{239} or U^{233} would probably require a change in rod speed. On the other hand, if the reactor is assumed to go beyond prompt critical, the substitution of these fuels would make little difference. For example, Newsom's criterion (*2*) would result in the same rod speed regardless of fuel.

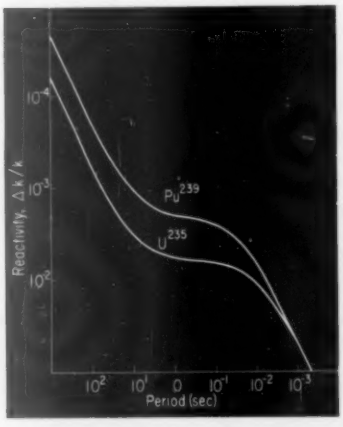


FIG. 2. Reduced delayed-neutron fraction of Pu^{239} has this effect on period-vs-reactivity characteristic

Stability

Certain reactors, notably the Borax reactors, the Experimental Breeder Reactor and SPERT-1, have exhibited

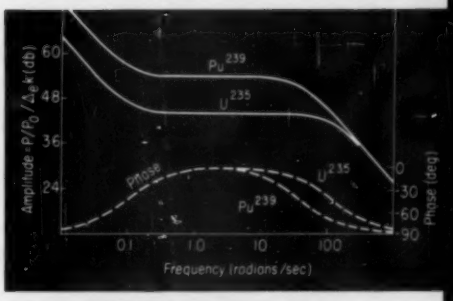


FIG. 4. Inherent frequency response of hypothetical reactor fueled with either U^{235} or Pu^{239}. Prompt-neutron lifetime is 5×10^{-5} sec. Shown is $K_1G_1(j\omega)$, the response of the bare reactor without feedback

tendencies to oscillate. Such behavior, which can be attributed to some kind of feedback, is termed unstable if the oscillations become self-sustaining. Standard methods for investigating feedback systems have been applied in investigations of these reactor stability problems. The best known of the techniques, the frequency-response method, has been used to investigate experimentally the stability of EBR (*3, 4*), EBWR and Borax-4 (*5*). (See box on page 69 and Figs. 3–5.)

What is the effect on stability of using fuels other than U^{235}? In the frequency range of interest the gain of the reactor K_1G_1 is inversely proportional to β, the fraction of the fission neutrons that are produced with delay. This is illustrated by Fig. 4 and the data in the table on page 68. It follows that a reactor that becomes unstable at 60 Mw when using U^{233} would become unstable at 20 Mw if Pu^{239} were used instead—assuming that feedback is linear. While there is no assurance that the feedback is linear in real systems, it seems safe to say that the effect of using U^{233} or Pu^{239} will be deleterious insofar as stability is concerned.

Preferential xenon burnout leads to another type of instability—oscillations in the flux distribution (*6–8*).

Short-Term Transients

One important control problem is the short-term transient response of the system. By "short term" is meant times less than several minutes. A system must be stable; it must also have an acceptable transient response such that overshoots in temperature and pressure do not damage the system.

Short-term transients are produced

by such disturbances as load changes, xenon burnout, introduction of cold coolant, and loss of coolant flow.

Load disturbances. The approaches that have been taken toward load disturbances can generally be classified as either preventive or corrective. In the former an attempt is made to isolate the reactor so that disturbances are prevented from being reflected back to the reactor.

The second or corrective approach is the more common. The system is designed to take corrective action in response to the disturbance and match reactor power to load. Examples are HRT, SRE, APPR, PWR and the Enrico Fermi Reactor.

In general, reactors that use pressurized water as the coolant have an inherent control system adequate to accommodate load changes. Examples are HRT (*9*) and APPR (*10*). However, it has been pointed out that in marine applications, where it may be necessary to go from full ahead to zero to full astern in tens of seconds (*11*), an external control system would also be required in pressurized-water plants. It is not inconceivable that some land-based plants will require the same response. An oil-fired plant has been required (and built) that goes from 5% to nearly full load in as little as 3 sec (*12*).

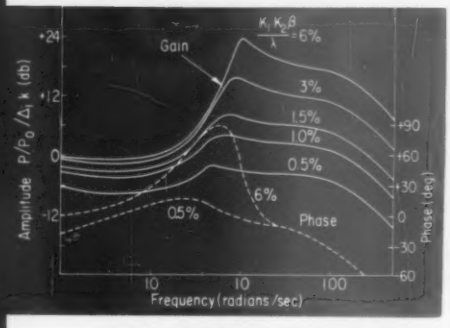


FIG. 5. Closed-loop response of hypothetical U^{235} reactor. Feedback consists of two first-order lags with 0.3-sec time constants. Gain curves are normalized to 0 db at $\omega = 0$

On the other hand, liquid-metal-cooled reactors must rely on external control systems to accommodate load changes as evidenced by SRE and the Enrico Fermi Reactor.

It has been suggested in the past that natural-circulation boiling reactors with sufficient heat capacity can be equipped with an external control system to accomplish load matching (*13*), thereby eliminating one need for steam dumping. Of course, the steam dumping system is still required in the direct cycle for pressure relief. Operating experience with EBWR has indicated that this reactor can be made to perform satisfactorily with an external control system.

Loss of coolant flow. A conceivable accident that limits the design of many reactors is loss of coolant flow. The only kinds of reactors that appear to have inherent control systems capable of accommodating loss of coolant flow are circulating-fuel and homogeneous reactors.

In most forced-convection, single-phase, liquid-cooled, heterogeneous reactors it is necessary to scram the reactor on loss of coolant flow to limit pressure and temperature surges to safe values. However, calculations performed on the APPR design indicate that under certain conditions this reactor is an exception (*14*). This may be due in part to its relatively low power density (90 kw/l of coolant) and the fact that the primary coolant system is designed to remove a significant amount of power by natural circulation.

An interesting aside in connection with this problem is that it has been found in the SRE design (*15*) that shutting down the reactor too quickly after loss of the pumps will result in excessive thermal stresses. As a result, only one rod is scrammed rather than all the rods.

Coolant flow in natural-circulation boiling reactors can be lost if the water level in the reactor vessel is allowed to drop below the top of the riser. The most serious consequence is that the reactor will become unstable. This was borne out by the "teapot experiment" conducted on Borax-4 (*5*). However, this does not appear any more serious than loss of flow in other reactor types, in that there is ample warning to scram the reactor. To prevent such an accident, the EBWR has a low-water-level scram.

Cold-coolant accident. A reactivity disturbance can be produced by the introduction of a cold slug of coolant into the core when the coolant has a negative temperature coefficient of reactivity. This accident is most serious in water-cooled reactors because of their larger coolant-temperature coefficients of reactivity. Here the approach is to prevent such an accident through interlocks.

Subcooled or pressurized homogeneous reactors are somewhat better equipped than heterogeneous subcooled reactors to cope with the cold-coolant accident. This is because homogeneous reactors have a larger volume of coolant in the core. Natural-circulation boiling reactors are even better off in that it is practically impossible to get a slug of cold water into the core.

Ceramic fuel elements. The use of ceramic fuel elements can have a pronounced effect on short-term transient response of systems that depend on an inherent control. Such fuel elements have received considerable attention in systems where it is pro-

Delayed-Neutron Groups* from Three Reactor Fuels

	U^{235}		U^{233}		Pu^{239}	
Group	λ_i†	β_i‡	λ_i	β_i	λ_i	β_i
1	3.01	0.00027	2.50	0.000085	2.70	0.000092
2	1.14	0.00073	1.13	0.000128	1.12	0.000181
3	0.301	0.00254	0.325	0.000695	0.325	0.000685
4	0.111	0.00125	0.139	0.000630	0.124	0.000443
5	0.0305	0.00140	0.0337	0.000747	0.0301	0.000626
6	0.0124	0.00021	0.0126	0.000215	0.0128	0.000073
Total (β)		0.00640		0.002500		0.002100

* Computed from reference *19*.
† λ = reciprocal of mean life (sec^{-1}).
‡ β = delayed-neutron fraction. Values of β are actual rather than effective yields. Effective yields take into account energy difference at birth between prompt and delayed neutrons.

posed to load significant quantities of thorium or U^{238} in the reactor. The reason for their effect is that their time constant or thermal lag is longer than for metallic fuel elements. For example, a ½-in.-dia fuel element with a UO_2 matrix has a time constant of ~10 sec. On the other hand, the time constant of a thin metallic plate-type element is so small as to be negligible. Therefore, the effect of using ceramic elements is to introduce an appreciable lag in the system, which will degrade the short-term transient response and increase overshoot. Substitution of an all-ceramic core for an all-metallic core can result in the necessity for an external control system in a reactor that would not otherwise require one.

The preceding statements ignore the Doppler effect that exists in low-enrichment systems. However, the reactivity change produced by the Doppler effect is small compared to the reactivity change produced by a change in coolant temperature. Thus the Doppler effect can be neglected in the first approximation if the fuel-element time constant is the dominant one—which means the longest one. However, the Doppler effect will influence the steady-state programming problem as mentioned later.

Long-Term Transients

A reactor is also subjected to long-term disturbances where "long-term" denotes times of the order of days; the two most important are xenon buildup and fuel burnup.

Xenon buildup is not much of a problem and is usually compensated for by manual changes in rod position. Of course, in a fast reactor, Xe^{135} is no problem at all since it has a large cross section only for slow neutrons.

The problem of fuel burnup is more serious in that the accompanying decrease in reactivity may limit core lifetime. The techniques available for maintaining reactivity include use of burnable poisons, U^{238} and thorium (*16*, *17*).

The effect of these materials on long-term reactivity is illustrated by the sketches in Fig. 6. The reactivity of a highly enriched core decreases with time due to fission-product buildup. Assuming that corrosion and radiation damage are not limiting factors, the core life will be limited by total control-rod worth. That is, as fuel is burned, reactivity decreases and must be compensated for by withdrawing control rods. When reactivity decreases to the point where the control rods have been completely withdrawn, the core must be replaced.

The use of burnable poison, as in the APPR, extends the core life as indicated in Fig. 6. However, this scheme requires a higher initial loading of fuel and has a poor neutron economy.

U^{238} has somewhat the same effect as burnable poisons in that reactivity initially increases due to plutonium buildup (assuming the system has a significant conversion ratio). Ultimately, reactivity decreases with fission-product buildup.

The curve of reactivity as a function of time for a thorium system shows an initial decrease in reactivity. This comes from the longer delay in the conversion of U^{233} from Th^{232} as compared with the conversion of Pu^{239} from U^{238}. However, as shown, reactivity in the thorium system does increase after the initial dip. Here again, though, the curve is applicable only to systems with a significant conversion ratio. Although not shown in Fig. 6, reactivity eventually decreases with time in this system as well because of fission-product buildup.

It has been suggested that the curve of reactivity vs. time can be flattened by using a combination of U^{238} and thorium. The reasoning behind this is apparent from Fig. 6.

As for current practice, the APPR uses burnable poisons, the PWR and EBWR use U^{238}, Borax-4 and HRT use

Frequency-Response Analysis of Reactors

A reactor system can be characterized by its steady-state response to a small sinusoidal forcing function as illustrated in Fig. 3. The forcing function must be small so that the kinetic equations can be treated as linear. It can be created by oscillating a control rod. Figure 4 shows the frequency response of a reactor with neither inherent nor external feedback. This is $K_1G_1(j\omega)$ in Fig. 3. Fig. 5 shows the closed-loop response of a hypothetical reactor.

Peaking is the ratio of the maximum closed-loop amplitude to the amplitude at zero frequency. When peaking is infinite, the system will sustain oscillations. This suggests measuring peaking at different power levels and plotting reciprocal peaking against power. Extrapolation to zero shows the maximum power at which the system is stable.

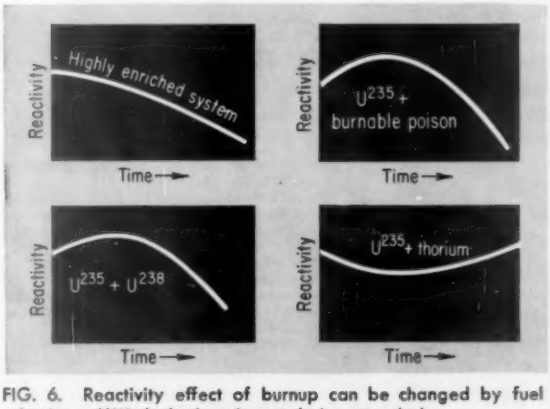


FIG. 6. Reactivity effect of burnup can be changed by fuel selection. U^{235} + thorium time scale is expanded

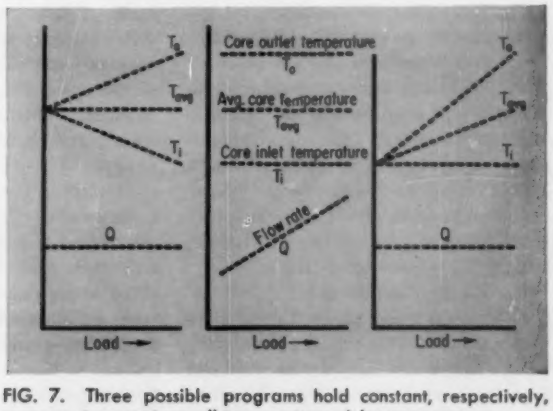


FIG. 7. Three possible programs hold constant, respectively, average temperature, all temperatures, inlet temperature

Inherent Feedback in a Pressurized-Water System

A pressurized-water reactor is an impressive example of inherent feedback. The variable θ of Fig. 1 would represent average coolant temperature in the core. If load is increased, steam flow to the turbine increases; thus, steam pressure and hence steam temperature decrease. This cools the primary water leaving the heat exchanger, which causes the inlet temperature at the core to decrease, which in turn reduces the average temperature of the coolant in the core. In terms of Fig. 1, $\Delta_2\theta$ becomes negative as the load is increased.

Because the reactor has a negative temperature coefficient, the decrease in θ causes reactivity and thus reactor power to increase. The increase in reactor power heats the water in the core, causing an increase in θ. This is a positive $\Delta_1\theta$. Thus the system tends to be self-regulating; when equilibrium is reached, the decrease in θ ($\Delta_2\theta$) caused by increasing load is compensated by an increase in θ ($\Delta_1\theta$) produced by an increase in reactor power. The net change is zero. If the inherent feedback is large enough, no external control system is required.

thorium, and the reactors for Consolidated Edison and Commonwealth Edison will use U^{238} with some thorium. The curves in Fig. 6 are for heterogeneous cores and do not necessarily apply to homogeneous systems.

A long-term reactivity disturbance peculiar to homogeneous systems is the so-called "walk-away" problem (*18*). This is the increase in fuel concentration, and hence reactivity, caused by radiolytic gas production. However, it does not appear to be a serious problem and can be corrected directly by suppressing gas evolution.

Steady-State Programming

A final problem is how to program the important plant variables with respect to load. Programming problems are generally the same whether the reactor is homogeneous, heterogeneous, liquid-metal-cooled or water-cooled as long as cooling is by forced circulation. Reactivity follows average temperature if the coolant temperature coefficient of reactivity is much larger than that of the fuel. Therefore a constant-average-temperature program is a constant-reactivity program.

In a boiling reactor, however, reactivity is proportional to average coolant density. Thus a constant-reactivity program requires operation over a very large pressure range. Low-enrichment fuels present special problems because of the Doppler effect, which will be discussed later.

Forced convection cooling. Reactors that are cooled by forced convection include one or more circulating pumps for the primary coolant and one or more heat exchangers for transferring heat from the radioactive primary loop to the nonradioactive secondary loop. In general, steam is generated on the secondary side of the heat exchanger and used as the turbine fluid. The problem is: What is the best method of regulating coolant flow rate, average core temperature, and coolant temperature rise across the core with respect to load?

Three possible systems are shown in Fig. 7. In the first, the flow rate and average temperature are constant, and inlet and outlet temperature vary symmetrically about the average. In the second, all temperatures are held constant by varying the flow rate. In the third, inlet temperature and flow rate are constant and outlet and average temperatures are allowed to vary.

A variable-temperature system is undesirable because of thermal stresses produced by changing the temperature and because of pressure surges. Furthermore, a system in which the average steady-state core temperature changes does not exploit the temperature coefficient of reactivity. On the other hand, a constant-average-temperature system results in variable steam temperature and pressure because of the temperature drop across the heat exchanger. This is undesirable from the standpoint of the secondary system design.

Finally, a system with a constant temperature rise across the core requires that the coolant flow rate vary, which is an added complication. Thus, there is no panacea to the programming problem, although certain trends can be recognized in systems presently built or well under way. The methods used in practice are summarized in the table on page 71 of this report. Some of the systems listed as having a constant coolant flow rate have, in fact, two-speed pumps. However, in essence these are constant-flow systems.

Boiling reactors. In a boiling reactor using natural-circulation cooling, constant reactivity requires a very large pressure range. Under constant-coolant-density conditions, it has been suggested that reactor power will automatically match load (*15*). Because the pressure variation required is so large as to be impractical, all boiling reactors to date have operated with constant-pressure and variable-reactivity programming.

Forced circulation offers an out to this problem. The amount of subcooling can be varied enough to provide both constant-pressure and constant-reactivity programming.

Low-enrichment fuels. The preceding discussions have neglected the Doppler effect, which will be a factor in systems using low enriched fuel. It causes reactivity to decrease as fuel temperature increases. A typical variation in reactivity over the power range is $0.15\%\,\Delta k$. In a water system, with a coolant temperature coefficient of reactivity of say -2×10^{-4} $\Delta k/°$ F, the average coolant temperature would have to change 7.5° F to compensate for this. Thus to maintain a constant-average-temperature program, reactivity must be varied by means of an external control system.

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Reactor Control Strategies

Operational control strategies for power reactors are dictated by reactor type but are implemented in many ways, a NUCLEONICS survey shows

REACTOR CONTROL STRATEGIES, *when grouped by reactor type, are seen to follow generic lines. Thus pressurized-water reactors use a constant-T_{avg}–constant-flow program, and gas reactors use a constant-temperature–variable-flow program.*

Within these broad categories each reactor group interprets control strategy in its own way. As part of its survey of design specifications for power-reactor control systems around the world, (see p. 74), NUCLEONICS *asked for a summary of the control approach employed. The survey information about control strategies is summarized in the table on the following page. Detailed comments as provided by some of the reactor groups follow.*

Pressurized-Water Reactors

Operators and designers at pressurized-water reactors find their control systems simple and effective. In particular an experiment with the Army Package Power Reactor backs up these observations dramatically (see box, p. 73).

Yankee. The advantage obtained through the use of a constant-average-temperature control program for pressurized-water reactors is that, in most cases, these plants are self-regulating through the moderator's negative temperature coefficient of reactivity. As a result, rod action is needed only to limit the peak of large transients, and the duty of the reactor control system and rod-drive mechanisms is kept to a minimum. Moreover, the duties of various systems of the primary reactor plant, such as the pressurizer and the feed and bleed systems, are also minimized through the use of a constant T_{avg} program.

Shippingport (PWR). Most normal load changes, usually not over 20% of full power, are accommodated by the inherent negative temperature coefficient of reactivity. Principal use of the control rods is to adjust for slow reactivity changes (such as xenon) to hold average temperatures constant.

Although an automatic reactor control system is provided, the reactor has undergone a 100% stepwise reduction in power demand (turbine-throttle trip) while under manual control without exceeding any design operating limits (NU, Apr. '58, p. 71). The pressurizer-spray control was operative and system relief-valve settings were not reached. Coolant temperature did not reach the alarm point.

The automatic control system used in PWR to maintain T_{avg} is typical of many pressurized-water reactors: the system uses the reactor inlet and outlet temperatures in the basic error signal with rate of change of reactor neutron flux as a damping signal. Thus, control-system error signal T_{error} is given by

$$T_{error} = 523 - \tfrac{1}{2}(T_{outlet} + T_{inlet}) - K\, d(\log N)/dt$$

Control-rod action is initiated at T_{error}, as computed above, and is $\pm 3°$ F.

NPD-2. Among pressurized-water reactors, the control system for the Canadian NPD-2 reactor is the most unusual. Reactivity is controlled principally by changing the temperature and volume of the moderator. (There is in addition a single slow-moving enriched rod, worth about 33¢.) Moderator volume control performs the usual function of regulating and shut-off rods. Both volume and temperature control compensate for xenon.

The moderator volume is connected at the bottom through a "weir-action" port to a dump tank. The moderator is supported by a differential helium gas pressure between the moderator cover space and the dump tank. A parallel system of helium blowers and regulating valves maintains the pressure difference. Under steady-state conditions the regulating valves are open enough to pass just the capacity of the blowers (which run at constant rate). Pumps lift moderator from the dump tank to the core at a rate equal to the flow through the weir-action port.

Movement of the regulating valves from their steady-state position establishes a rate of change of differential pressure. The moderator level follows through a change in port flow. The maximum positive reactivity rate due to change of moderator volume is limited by blower capacity. Dump valves are also provided. They can be opened in 0.5 sec by protective circuits and are large enough that the moderator tank empties in about 12 sec.

Gas-Cooled Reactors

In contrast to pressurized-water designs, the gas-cooled reactors rely heavily on automatic external control systems to hold parameter values. These systems vary gas flow, control-rod position and pressure of low-pressure steam to maintain constant reactor power and constant gas inlet and outlet temperatures.

Berkeley (England) power station. When starting up or shutting down, control of the rods is manual. Under operating conditions the rods are controlled so as to keep gas-outlet temperature at a preset value.

Station output is varied by altering the turbine-throttle settings and simultaneously adjusting the gas mass flow to maintain h.p. steam pressure at its normal operation value. The turbine h.p. and l.p. throttle valves are ganged so that the l.p. steam pressure is allowed to vary with different h.p. throttle settings. This variation is calculated so as to maintain the reactor gas-inlet temperature at all loads.

Gas is circulated through the eight boilers by means of eight single-stage axial-flow gas circulators. These are driven by eight induction motors supplied from the station auxiliary bus bars. Circulator speed is varied by a hydraulic coupling between the circu-

lator and its driving motor. The power transmitted by these couplings is varied with a ganged controller from the central control room.

Boiling-Water Reactors

The boiling-water reactors also are provided with fairly elaborate control-loop systems.

Dresden is to be controlled by means of a turbine-speed governor and a pressure regulator. These two controls are tied together by a special control-linkage system to operate the primary-turbine admission valves, the primary-steam-bypass valves and the secondary-turbine admission valves. The pressure regulator holds essentially constant pressure in the reactor vessel to prevent reactivity changes arising from pressure fluctuations. Primary steam is admitted to the turbine in sufficient quantity to hold the set pressure. If the turbine cannot accommodate this required steam flow, the bypass valves open and the excess steam is passed to the condenser. The speed-governor mechanism admits secondary steam to the turbine to complete the total turbine requirements and control reactor-inlet-water subcooling to maintain reactor power at the proper level. The system is an all-hydraulic control operated from the turbine-oil supply.

A backup pressure regulator is provided to override the main pressure regulator if the latter should fail and allow the system pressure to rise. In addition to this linkage tie-in between primary and secondary valve openings, another connection between primary and secondary steam flow is used as a mechanism of void control. As the load on the turbine is increased, more secondary steam is admitted to the turbine, subcooling at the core inlet from the primary side of the secondary heat exchanger is increased, and boiling occurs at a higher level in the core. The effective reactivity in voids is diminished, core-power output increases and primary steam and steam voids build up. Void reactivity builds up to the value before the load change. By this means load control in the range of 40–100% of full load is effected automatically by changes in secondary steam flow, without any control-rod repositioning.

EBWR. Since the EBWR system includes an automatic steam-bypass valve, the general policy for routine

TABLE 1—Steady-State Programs Used by Today's Reactors

Reactor (for location see pp. 74–77)	*Fixed parameters* (value does not change with load)*	*Load-dependent parameters* (value is fixed during steady-state operation but changes with load)*	*External control loops (automatic unless noted)*	
			*Activating signal**	*Compensating response*
Pressurized-water reactors				
APPR-1	T_{avg}, V_c	T_i, T_o	T_{avg}	rod motion (manual)
PWR	T_{avg}, V_c, P	T_i, T_o	T_{avg}, flux	rod motion
			P	pressurizer heaters or sprayer operation
NPD-2	T_{avg}, V_c, P_s	T_i, T_o	P_s	liquid-moderator level change
BR-3	T_{avg}, V_c	T_i, T_o	T_{avg}, flux	rod motion
Yankee	T_{avg}, V_c	T_i, T_o	T_{avg}, flux	rod motion
Gas-cooled reactors				
Berkeley	T_o, T_i, P_s (h.p.)	V_c	T_o	rod motion
Calder Hall			station load	gas-circulator speed
Bradwell				
Hunterston			T_i	l.p. steam-pressure throttle adjustment
EDF-1	I_o, I_i, P_s	V_c	T_o	gas-flow change
G-2				
G-3			flux	rod motion
Boiling-water reactors				
EBWR	P, V_s	(natural circulation)	P	bypass valve operation
Dresden	T_o, P	V_c, T_i	P	bypass valve operation
			station load	change l.p. turbine throttle and feedwater subcooling
Sodium-cooled reactors				
EBR-2	T_i, P_s	T_o, V_c	flux	rod motion
			T_o	change V_c (manual)
PRDC	V_c	T_o, T_i	T_o	rod motion
SRE	T_o, T_i	V_c	T_o	change pump speed
			T_i	change feedwater flow
Homogeneous reactors				
HRE-2	P, V_c, T_{avg}	T_i, T_o	P	operate condensate heaters
			T_{avg}	change fuel concentration

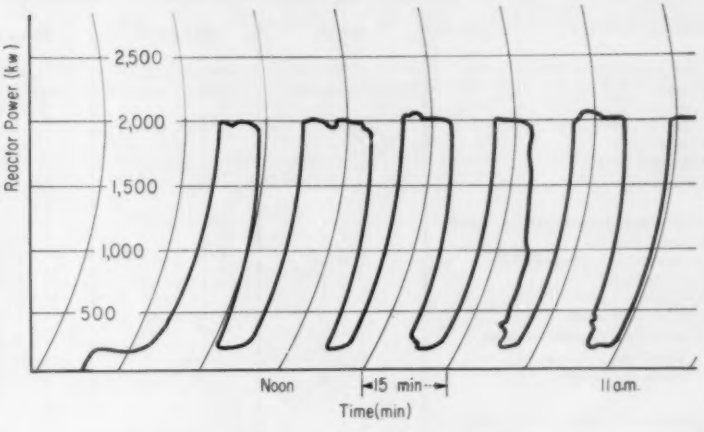
* Definition of parameters in table: T_o = reactor-coolant outlet temperature, T_i = reactor-coolant inlet temperature, V_c = reactor-coolant flow, P = primary-system pressure, P_s = secondary-system steam pressure, T_{avg} = average reactor-coolant temperature, T_s = fuel-element surface temperature, V_s = steam flow.

operation is to maintain a constant steam flow, not a constant pressure. A small variation in pressure (about 10 lbs) is tolerated at all times, the pressure variation being used to adjust the steam flow to the reactor output.

Under these circumstances, the load is dependent upon the power of the reactor. By closing the bypass the reactor can be run so that the reactor power follows the load as would be true in a power plant. Under these conditions, the operator is aware of the steam flow, the pressure, and the electrical kilowatt load. He can easily hold the reactor at pressures within about 10 lb of the desired 600 psig by moving the rods in discreet amounts of about ¼ in. at widely spaced intervals. In time the heat capacity of the system and the negative temperature coefficient of the water tend to stabilize the over-all plant so that continual rod-adjustment to off-set pressure variations is not necessary.

The large thermal capacity of EBWR would make it easy to install an automatic rod-positioner. In fact, such a system is presently planned as an experiment but, because of the little need seen for it, no accelerated effort is being made. Were a boiling reactor to be operated as an isolated plant, the ability to follow load changes would considerably inhibit the plant operation, unless an automatic system were available.

Reactor Outshines Generator in APPR Load Response



APPR generator output trace taken during recent demonstration of system stability. Generator load was cycled from full load to no load six times within two hours. During this time reactor was controlled entirely by negative temperature coefficient—no control rods were moved. Resulting temperature and pressure transients were quite moderate. Operators find load response is limited more by turbine-and-generator response than reactor response.

Sodium-Graphite Reactors

SRE. The Sodium Reactor Experiment operates at fairly high temperatures with large temperature differences in the system (500° F inlet and 960° F outlet). Due to the high thermal conductivity of the sodium coolant, and the high film coefficient associated with it, any change in sodium temperature is very quickly reflected by corresponding temperature variations in the piping, tank walls, heat exchangers and other system components. In order to minimize the resultant thermal cycling, the SRE is operated with fixed inlet and outlet temperatures, and sodium flow rates are varied as the power level changes.

Fast Breeders

EBR-2. The primary-system flow rate is regulated at any given power level to provide a predetermined reactor-coolant outlet temperature, varying from 900° F at full power to 850° F at very low power. This 50° F variation in reactor-coolant outlet temperature provides for a constant steam temperature of 850° F at all power levels.

Irrespective of reactor power level, the temperature of the cold leg of the secondary system automatically remains between 580° F and 610° F. This is because the temperature of the evaporator water is kept constant and the design and capacity of the evaporator are such as to effect a very small approach temperature at the sodium outlet end. Also irrespective of reactor power level, the temperature of the hot leg of the secondary system remains relatively constant, varying from about 880° F at full power to about 850° F at very low power (reflecting control of the reactor-outlet coolant temperature). Consequently, the rates of heat removal from both the primary system and the secondary system become approximately proportional to the secondary-system flow rate.

Homogeneous Reactors

The control philosophy of homogeneous reactors is the most unusual—these reactors do not need control rods.

HRE-2. In Homogeneous Reactor Experiment-2 control is applied to the fuel temperature by regulating the uranium concentration of the circulating fuel. Power level control is manual, depending simply on the heat removal rate (turbine governor–controlled) set by the operator. With this type of reactor system, the philosophy is to control only the reactor pressure and temperature. The reactor pressure results from the application of electric heaters to a condensate tank.

The condensate heaters are turned on and off automatically to maintain a previously set pressure. The temperature of the circulating fuel, although dependent on the concentration of uranium, must be controlled within limits to prevent the chemical instability that might result at excessive temperatures. In a sense, the concentration-control system of the homogeneous reactor is equivalent to the control rods of solid-fuel reactors. Likewise, the dumping of the liquid in the high-pressure system of the homogeneous reactor is equivalent to a scram in the other system.

Power-Reactor Control the World Around—

BOILING WATER

Reactor	Arbor	Borax-4	Dresden	EBWR	VBWR
Location	Arco, Idaho	Arco, Idaho	Morris, Ill	Lemont, Ill.	Vallecitos, Calif.
Type	boiling water	boiling water	boiling water	boiling water	boiling water
Output					
Mw(th)	200	14.5	625	20*	30
Mw(e)	0	2.0	180	5*	6.8*
Manufacturer	Argonne	Argonne	GE	Argonne	GE
Date on line	1960	Jan. 1957	1960	Dec. 1956	Aug. 1957
Control requirements—new or equilibrium core (%Δk/k)					
Temperature compensation	0.46	3.2*	1.0	0.67	0.0
Equilibrium xenon	3.1	1.8†	3.0	2.2	3.1
Xenon override	1.1	2.7†	0		1.0
Equilibrium samarium	0.9	0.659	1.0	0.75	0.7
Other reactivity allowances	8.0*	‡	4.5*	3.51†	2.5†
Total requirement[1]	~13.5	—	9.3	7.13	7.3
Total rod worth	~16.5	7.5	15.6	12.4	10.5
Parameters of actual control system					
Xenon poison interval[2] (hr)	32†	6–8†	0†	0	~15
Range, electric power (Mw)		0–2	72–180	0–5	0–5
Accuracy, electric power (kw)		±100			
Response time (sec)			180‡		0.10
Emergency shutdown time (sec)	~1	0.5		0.35	0.25
Size of neutron source (n/sec)	$>10^{10}$	4×10^8	10^8	$>10^{10}$	10^7
Control rods					
Shape	cruciform‡	blade	cruciform	cruciform	blade
Number	9	5	80	5 | 4	7‡
Absorber section					
Composition	2% B in ss	boral & Hf tip (4) Al-clad Cd (1)	2.0% B in ss	Hf | 2% B in 304 ss	B_4C blocks in ss§
Length (in.)	72	49	102	46	43
Fuel section	(none)	(none)	(none)	(none)	(none)
Stroke (in.)	72	25.5	106	48	42
Weight, each rod (lb)	320	200	155§	97 | 141	30, 60‡
Withdrawal rate (in./min)	18	12	360	28	4 or 12
Insertion time (sec)					
Normal	240	127.2	18	~1,000	600,200
Emergency	~1	0.50	2.6	0.35	133¶
Rod drives					
Type	rack and pinion		locking hydraulic piston¶	lead screw and nut	lead screw and nut‖
Number	9	5	80	9	7
Power requirement					
(volts)	440	440		440	120
(no. of phases)	3	3		3	(d-c)
(amperes)		0.55		0.8	
Motor rating					
(horsepower)	0.33			0.33	0.5
(rpm)	1,750	47.8		68	1,725 or 125
Position-indicator accuracy (in., ±)	0.025	0.01	8.8	0.025	0.004

[1] Control requirements are not strictly additive. Thus total requirement is not always the sum of individual contributions.

[2] Question asked was, "Length of interval in which xenon makes reactor inoperable after shutdown from design load?"

Arbor. *Steam voids, 2.0. †If peak operating xenon level is reached. ‡10-in. × 10-in. × ¼-in. cross.

Borax-4. *80°–417° F, 300 psig. †For 8-Mw operation. Initial max power is 4.5 Mw. ‡Balance for burnup and voids.

Dresden. *Voids, 2.3; burnup 2.0. †Some reduced-power operation required. ‡40%–100% full power. §Absorber section only. ¶Driving force for all control-element movement is derived from accumulators backed up by vessel pressure.

EBWR. *Design power. Reactor has operated at 61.7 Mw(th) (NU, April '58, p. 25). †Voids and burnup.

VBWR. *Turbine generator limited to 5-Mw output; remaining 1.8 Mw dumped to condenser. †Voids 1.5, fuel burnup 1.0. ‡One rod is a 5.75-in. blade weighing 30 lb; six are 12-in. blades weighing 60 lb each. §2⅞ × 2⅞ × ¼-in. blocks. ¶Not scram. ‖Top-entering electro-pneumatic similar to those on Borax-3. Drive is d-c motor through chains to 2 vertical lead screws. During scram 200-lb air is applied to upper portion of air cylinder.

ALPR. *In addition 400 kw of space heating is provided. †Voids and burnup. ‡Critical operation to cold condition. (Control requirements are not strictly additive.) §Figures indicated are for 5 cruciform rods and reference core of 40 fuel assemblies. Maximum core will have 4 additional T-shaped rods and a total rod worth of 20%. The T-shaped rods weigh 37 lb each. ¶Complete xenon override for 75% of core life.

APPR. *Fuel burnup, fission products, residual burnable poison. †With 5 rods; 24.6 with 7 rods. ‡Transient xenon will make reactor inoperable only at end of life. Time estimate is complicated by fact system cools off following shutdown, introducing reactivity. §2.65 × 2.65-in. square water-filled tube has 4 absorbing plates in absorber section and 16 fuel plates in fuel section. Absorbing plates have 0.09-in. meat thickness with 0.033 in. of 304L-stainless-steel cladding. ¶1 centerline, 4 in a ring, 2 close packed (NU Reactor File No. 2, Aug. '57). ‖This is meat composition. **22 × 2.281-in. fuel section has

Responses to a NUCLEONICS Questionnaire

PRESSURIZED WATER — SGR

ALPR	APPR	BR-3	NPD	PWR	Yankee	SRE		
Arco, Idaho boiling water	Fort Belvoir, Va. pressurized water	Mol, Belgium pressurized water	Des Joachims, Ont. pressurized water	Shippingport, Pa. pressurized water	Rowe, Mass. pressurized water	Santa Susana, Calif sodium-graphite		
3	10	43	81	231	482	20		
0.3*	1.825	11.5	22	60	134	6.5		
Argonne 1958	Alco April 1957	Westinghouse 1959	Canadian GE 1961	Westinghouse Dec. 1957	Westinghouse 1960	Atomics Int'l. April 1957		
2	5.0	8.4	1.0	3.0	7	0		
2.3	2.2	3.3	2.3	3.0*	5	2.18		
0	0.6		0.7	3		0.32		
0.7		0.9		1.0	1.0	0.6		
4†	8.2*	5.3*	0.05*	10†	6*	0.18*		
~8‡	16.0	17.9	4.0	20.0	19	3.28		
14§	19.0†	16†	~100†	25.0	14†	~10.0		
0¶	0‡	0‡	35	0‡	0‡			
0–0.3			0–22	5–60§				
		~5	540‡	~5¶	±1	0.75†		
<2	0.7	0.66–3.0	6§	1.3‖	~5§	~0.07		
10^9	3.8×10^7	1.2×10^8	(none)	10^{9}***	10^8	9.6×10^7		
						Shim	*Shim-reg.*	*Safety*
cruciform§	square tube§	cruciform	(none)	cruciform	cruciform	cylindrical		
5§	7¶	12		32	24	2	2	4
Cd in Al-Ni alloy	2.9% B^{10} in Fe‖	Hf or Ag-Cd-In		Hf	Ag 80%, In 15% Cd 5%	2.5 wt.% B-Ni alloy in 304 and 316 ss		
32	20.81	52		71.0	90	72‡	72‡	56‡
(none)	**	(none)		(none)	(none)	(none)		
32	22	52		71.5	90	~90		
49	72			55		56	56	22
3	3	§		11	6	3.6	36§	36
0.6								
~600	440	§		~390	900	1,440	1,440	—
<2	0.65–0.70	0.6¶		1.8	0.85	—	—	0.6
rack and pinion	rack and pinion	magnetic jack	(none)	collapsible rotor	magnetic jack	¶	‖	**
5§	7	12		32	24	2	2	4
208	440	100‖		235	115	220		220
3	3	(d-c)		3	(d-c)	3	2††	3
0.6		15‖			10¶			
0.125	0.167			0.1		0.25	††	0.5
1,620	1,140			22		1,140	3,600	1,425
0.1	0 .100			0.152 or 1.5	3	0.015	0.015	0.015

16 fuel plates. Each plate has 0.020 in. meat, 0.005 in. 304L ss cladding on both sides. Meat composition is 26.11 gm U^{235} in UO_2, 0.0245 gm B^{10}, 91.56 gm 302L ss.

BR-3 *Fission-product poisons and fuel burnup. †At operating temperature. To provide a 5% cold clean shutdown, borated water is added to primary coolant. ‡Up to 5,000-hr of core life. §Cannot be specified until completion of transient analysis. ¶Not considering dashpot effect. ‖Holding-power requirement.

NPD. *For regulation. †Moderator level is controllable from full to empty tank. Freely moving booster rod (total worth 0.24% $\Delta k/k$) furnishes minimum poison override. ‡Zero load to full load. §Full power to 10% power.

PWR. *60 Mw net. †Fuel burnup. ‡It is estimated that reactor will be able to fully override maximum xenon for ~½% seed life. End of seed life (3,000 efph is design figure) will be determined by ability to override equilibrium xenon at design temperature. §Minimum value is good operating practice limitation. Turbine can operate at no load. ¶Transit time of coolant from heat exchangers to core is ~4–5 sec. Automatic-control-system's largest single factor in response time is that of resistance thermometers. Their response time is 3 sec to 63% of a step change in temperature. "Cold leg" temperature is sensed as close as possible to heat-exchanger exit. ‖<0.5 sec from sensing of a condition to unlatching of control rods. **Four 100-curie PoBe sources. Neutron-flux instrumentation will be able to "see" source for at least four half-lives.

Yankee. *Fuel burnup and fission-product poisons. †At operating temperature. To provide ~5% cold clean shutdown borated water is added to primary coolant. ‡Up to 7,000-hr of core life. §Time needed for rods to fall by gravity down full length of core. Does not include dashpot effect nor instrument time constant. ¶Approximate holding-power requirement.

SRE. *Doppler effect. †Control system flux servo. ‡Shim rods, 18 rings, 2.5-in. o.d. × 1.75-in. i.d. × 4-in. long. Safety rods, 14 rings, 2.3-in. o.d. × 1.9-in. i.d. × 4-in. long. §Regulating speed is limited to maximum of 15 in., corresponding to ~0.5% $\Delta k/k$. ¶Single-speed motor through gears and ball screw. ‖Two-speed motor through planetary gears and ball screw. **Chain drive with holding magnet. ††100 watts.

Continued, next page ➡

Power-Reactor Control the World Around—

GAS COOLED

Reactor	Bradwell	Calder Hall	EDF-1	G1	G2 and G3
Location	England	England	Chinon, France	Marcoule, France	Marcoule, France
Type	gas-cooled	gas-cooled	gas-cooled	gas-cooled	gas-cooled
Output					
Mw(th)	531	180	300	40	~150
Mw(e)	150	42	80	5	25–30
Manufacturer	John Thompson	UKAEA	Elec. de France	CEA	CEA
Date on line	1960	May 1956	1959	Jan. 1956	April, Oct. 1958
Control requirements—new or equilibrium core (%Δk/k)					
Temperature compensation	2.1	~1.6	2.1	0.7	1.8
Equilibrium xenon	1.8	~2.0	2.6	0.7	1.7
Xenon override	0.4	} 0.9	0.5	0	0.3
Equilibrium samarium	0		0.75	0.7	0.7
Other reactivity allowances	1.0*		1.7	0.1	
Total requirement[1]	5.3	~4.5	7.65	2.2*	4.5*
Total rod worth	7.0†	5.5	9.0	4.0	5.5
Parameters of actual control system					
Xenon poison interval[2] (hr)	‡		15	0	0
Range, electric power (Mw)	0–150		5–80		
Accuracy, electric power (kw)					
Response time (sec)			100–200		
Emergency shutdown time (sec)	3	~5	8	2	2
Size of neutron source (n/sec)	4×10^{10}§	*		5×10^9	5×10^9
Control rods			*Fine rods* | *Coarse & safety*		
Shape	cylindrical	cylindrical	hollow cylinders*	hollow cylinders†	hollow cylinders†
Number	120	~40†	52†	36	46
Absorber section					
Composition	Fe-B alloy in ss sheath	3–4% B steel in ss tubes	B_4C, steel clad	B_4C (5 kg)	B_4C (4 kg)
Length (in.)	252	264	118 | 236	198	198
Fuel section	(none)	(none)	(none)	(none)	(none)
Stroke (in.)	270	252	~335	294	265
Weight, each rod (lb)	230	130	66.1 | 92.6	44	44
Withdrawal rate (in./min)	0.5	0.5‡, ≦50§	240 | 0.24	0.197‡, 0.394§	0.197‡, 0.394§
Insertion time (sec)					
Normal	~420¶	300, 3,000	as req.	1,500‡	1,348§
Emergency	~5.5¶	5	8	720§	674§
Rod drives					
Type	variable-low-frequency‖	a-c motor, cable and drum¶	a-c motor and cable	asynchronous motors	asynchronous motors
Number	120	40	52	32	44
Power requirement					
(volts)	86**	40‖	127–220	127	127
(no. of phases)	3**	3	3	3	3
(amperes)			1.5	0.7	0.66
Motor rating					
(horsepower)	75	**	0.31	0.25	0.25
(rpm)	1,460		1,500	1,440	1,440
Position-indicator accuracy (in., ±)	1	1	0.4	0.4	0.4

[1] Control requirements are not strictly additive. Thus total requirement is not always the sum of individual contributions.

[2] Question asked was, "Length of interval in which xenon makes reactor inoperable after shutdown from design load?"

Bradwell. *System reactivity changes. †Additional long-term reactivity is taken up by steel absorber elements and fuel shuffling. ‡Xenon is a small factor. Minimum control-rod withdrawal time (7-hr) is such that xenon has passed its peak by the time criticality is reached. §Total of two sources. ¶Insertion rates: normal, 0.5 in./min; emergency, 4 ft/sec. ‖Two motor-generator sets supply 120 heads. **Motor-generator-set output.

Calder Hall. *Four SbBe sources producing a neutron power in the reactor of 2 watts. †Up to 60 in 112 available channels. ‡Coarse control rods. §Up to 4 rods used manually for fine control. ¶A-c motor driven transmitter for d-c synchronous servos. Slaves drive cable winches through 20:1 speed reducers. ‖0–1.3 cps. **200 watts.

EDF-1. *6-cm-dia rods in a square lattice. Absorber on outside is 0.4 cm thick. †Rods are in 3 groups offering reactivity control as follows: fine, 0.4% Δk/k; coarse 7.5%; safety 1.1%.

G1. *Excess reactivity is reduced by neutron absorption in thorium and activated nuclides. †Construction is identical with rods of G2 and G3. ‡10 central rods. §22 peripheral rods.

G2 and G3. *Excess reactivity will be reduced by neutron absorption in thorium. †Stainless-steel concentric cylinders, diameters 0.92, 1.04, 1.48, 1.59 in., B_4C between. ‡12 central rods. §32 peripheral rods.

Responses to a NUCLEONICS Questionnaire (*continued*)

FAST BREEDER ← **OMR**

Hunterston*	EBR-1	EBR-2	Enrico Fermi	OMRE
Hunterston, Scotland gas-cooled	Arco, Idaho fast breeder	Arco, Idaho fast breeder	Lagoona Beach, Mich. fast breeder	Arco, Idaho organic-moderated
530	1.2	62.5	300	12.4
180	0.2	20	100	0
GEC-Simon Carves 1961–1962	Argonne Aug. 1957	Argonne 1960	Power Reactor Dev. Co. 1960	Atomics Int'l Sept. 1957
1.9	*	0.4	0.15	4.88*
1.8	0			} 3.88*
0.4	0			
0	0			
1.0†	0	2.4*	0.32*	
5.1	—	2.8	0.47	8.76*
8.0	0.792†	5.0	6.69†	15.1*
0	0	0	0	
42–170	0–0.2	2–20	25–100	
1,800	1		1,000	
4‡		(manual control)		
8	0.3	0.4	0.75	
2×10^{11}		5×10^8	10^{10}	10^8
Coarse | *Safety* | *Fine*	*Moving blanket*‡ | *Safety plug* | *Control rods* | *Safety rods*		*Operating* | *Safety*	
cylindrical	cylindrical cup | plug in bottom of cup | 2-in.-dia. rods | 2-in.-dia. rods	hexagonal†	cylindrical | cylindrical	1.25-in.-dia cylindrical tubes†
158	1 | 1 | 4 | 8	12	2 | 8	6 pairs
boron steel	U^{238} | U^{235} | U^{238} | U^{235}	(none)	$B_4^{10}C$ & steel | $B_4^{10}C$ & steel	B_4C powder in ss tubes
256	30 | 5 | 30 | 30		8 | 33	36
(none)	(none)	‡	(none) | (none)	(none)
252	4.25 | 6 | 30 | 30	14	15 | 54	36, 5‡
110	8,000	~50	10 of $B_4^{10}C$ | 50 of $B_4^{10}C$	100
23 | 5 | 10	8.5§ | 1.1§ | 45§ | 45§	5§	0.3–3 | 2	
360 & 4,080 | 2,940 | 144 & 1,440	0.3¶ | | 3.84¶ |	120–180¶	300–3,000 | 1,620	2520
8 | 8 | 8	0.3–0.35¶ | — | — | 0.379¶		0.75	0.5
a-c motor, cable and drum	hydraulic elevator | air cylinder | worm & screw | rack & pinion	electro-mechanical||	servo with ball-out motion transducer | motor-driven; spring-acc. scram	rack and pinion§
158	1|| 1 | 4 | 8	12	2 | 8	6
18		230	115 | 220	208
3		3	1 | 3	3
5			3 | ~1	
0.125	7.5	0.25	0.033 | 0.25	0.125
160	1,165	1,800	2,000 | 1,800	1,620
2	0.001 | up or down | 0.001 | up or down	~0.01	0.03 | 0.25	0.05

Hunterston. *There are two reactors; figures are for one reactor. †Burnup. ‡For 1 % change.

EBR-1. *Temperature coefficient of reactivity is 2.76×10^{-5} % $\Delta k/k$/°C. †Total worth of outer blanket—upper 4.25 in. ‡All controls are located in the air-cooled outer blanket. For reactor configuration see NUCLEONICS, June '56, p. 35. Control and safety rods and safety plug are parts of outer blanket and their movement is relative to it. §Read "reactivity addition rate." Reactivity is added by inserting blanket material around core and decreased by removing it. ¶Read "reactivity withdrawal." ||Upper 4.25 in.—position controlled by 4 mechanical screw jacks.

EBR-2. *Permanent poisons, 0.2; Pu buildup −0.9; U^{235} burnup, 2.0; fuel growth, 1.1. †Each rod consists of 61 cylindrical fuel elements nested in a hexagonal container. ‡14.2-in. fuel section contains 21.3 % fuel, 20.8 % ss, 57.9 % Na. §Normal rate. In emergency withdrawal time is 0.4 sec. ¶120 sec to operation level; 180 sec to full insertion. ||With pneumatic scram and hydraulic shock absorber.

Enrico Fermi. *Burnup, 0.25; fuel-element growth, 0.05; fission-product poisons, 0.02. †2 operating rods have total worth of 0.69 %, which includes control margin of 0.22 %. 8 safety rods, used only for shutdown, are worth 0.75 % each.

OMRE. *450°–480° F. †Each pair of rods hangs from a common yoke and consists of hanger rod, removable snubber piston, rack coupling, kickoff spring. Overall length is 19 ft nominal. ‡Shim rods, 36 in. Regulating, 5 in. §Rotating pinion shaft is pressurized. Two racks can be operated through compound gear boxes at two rates. Fast rate for regulating rod action. Slow rate is shim rate described. Regulating motor is 100-watt 2-phase. Velocity is limited by voltage control.

A Look Ahead to Tomorrow In Power Reactor Control

By E. R. MANN, *Oak Ridge National Laboratory, Oak Ridge, Tennessee*

WHAT LIES AHEAD in power-reactor control? We can attempt a description by laying down a few rules to indicate the probable direction of reactor development. Once this is done, it is possible to make conjectures as to how control problems will be solved.

Most promising for the future are large stationary and small propulsion units

Fuel processing strongly influences land-based-reactor design in the direction of the large plant. Thus the problems that must be solved are those of big plants.

Reactors intended for special applications such as ship propulsion will be smaller and may have unusual control problems. Ship units for peace-time operation will have problems different from those for military purposes.

It is best, therefore, to assume that a look into the future is a look at control systems for these two applications.

One cannot take a particular design and assume that this is the nuclear power plant of the future. There appear to be many ways to design reactors for large base-load plants and propulsion units. Each design has its own control problems.

On the basis of these assumptions about future reactor types, one can make some predictions about the development of control systems. Some influences will make for simplicity, for example the simplification of the plant and the control problems associated with it. Some will make for more complexity, for example longer core lives and neutron spectra that change during reactor life.

Reactors will be designed so that hard-to-get information is not important for control

The purpose of a reactor control system is to make the reactor do what its designer had in mind for it to do. This suggests a control system with means for sensing every system variable and comparing with design values. But much of the information needed cannot be obtained. An example is fuel-element temperatures at all points. About the only solution is to redesign the reactor so that this type of information is no longer important to the control system.

This is done by operating fuel elements in in-pile tests in which operating conditions are equivalent to those of design until it has been determined that the fuel-element life is satisfactory if the rest of the system operates properly. The control system can then evaluate over-all performance instead of evaluating information on fuel-element temperatures.

Control-system design must avoid abrupt and unnecessary shutdowns

Unlike research reactors, power producers must operate at high temperatures to provide high efficiencies. Thus abrupt shutdowns can reduce the lives of components. Excessive temperature cycling over large ranges is bad.

The situation will be aggravated as more reactivity is made subject to automatic control. There will be more likelihood of over-power scrams, and more care must be taken to prevent them.

Temperature control will replace flux control through use of temperature coefficients

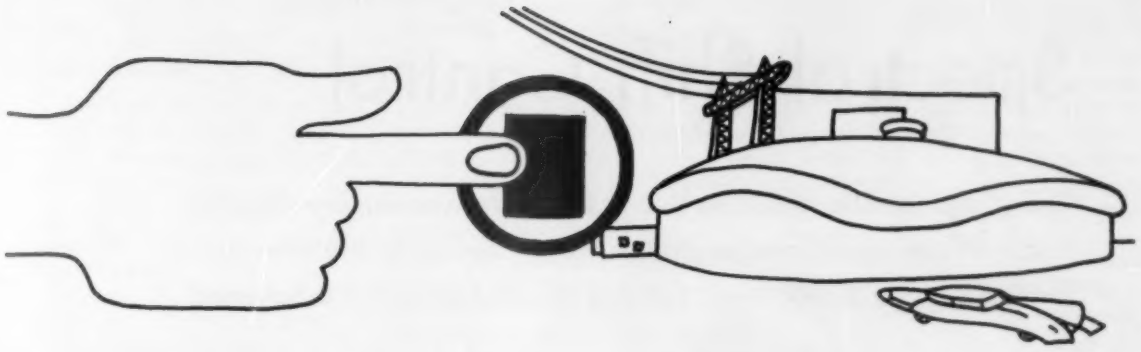
It is current practice to avoid designing power reactors with strong positive temperature coefficients of reactivity because of their inherent instability. On the other hand, failure of the control system for a reactor with a good negative temperature coefficient need not require immediate shutdown; in most designs it would lead to an orderly slow shutdown. It could be slow enough in fact to be treated as a scheduled shutdown. This then indicates that the temperature coefficient of reactivity can be used and will be used to convert the control system from one that controls neutron flux (as in the research reactor) to one that essentially controls some component's temperature in a power reactor.

Automatic control systems can be slower and, consequently, more reliable

Negative temperature coefficients can be used to simplify control systems. The result will be more reliable control equipment since, in general, slower, less complex equipment is more reliable than fast equipment. The job can be simplified by large heat-transfer coefficients, large heat capacities and large system inertia. Then large changes in neutron flux need not cause rapid and large changes in the controlled temperature. A slow-response control system can be used, and the neutron-flux signal can be used to anticipate the temperature-regulator action [E. R. Mann, *Trans.* PGNS-IRE, NS-3, No. 2, 12 (1956)].

Power densities in large plants will be low, leading to smaller temperature changes

To get long life from fuel elements it is sometimes necessary to design for low power density. Future power



densities are likely to be no more than 200 watts/cm³. This will reduce the danger of excessive temperatures with loss of coolant flow or a sudden change from laminar to turbulent flow.

The net result of low power densities, good heat transfer and large heat capacities is that rapid changes in fuel temperature are not required in the operation of the power plant and can only be effected accidentally by drastic changes in reactivity. Such changes would normally be taken care of by means of the safety system.

The objective is not to make control problems simpler, but they become simpler as a by-product of the resulting constant-temperature characteristic.

Reactor history and neutron spectrum may be inputs to control systems

Up to now operating-history information has not been needed for control. The control system has been made adequate for the initial prepoisoned reactor as well as for any later stage of its life.

However, there is considerable motivation to produce a reactor that will not require frequent refueling. One example is the use of burnable poisons in small plants. This affects the design of the control system, which must operate on information from sensors in the reactor. In principle the control system should have available the reactor history from the initial startup. This need will be greater as histories become longer.

History will be especially important in such control schemes as the spectral-shift method described by M. C. Edlund and G. K. Rhode on page 80 of this report. An analysis of the control problems for such a design may show that the accumulation of high-cross-section fission products creates a period of operation in which there are large positive power coefficients of reactivity, difficult to cope with. With accumulation of xenon considerable excess reactivity could be introduced as the xenon is burned out by thermal neutrons.

Neutron spectrum. A control engineer likes to measure what he is controlling. He dislikes a situation in which there may be latent trouble that can be detected only when it is too late to do anything about it. Continuous, rapid determination of the neutron spectrum may be a requirement for the control system of such a reactor. This might be done by sensing the moderator composition. Only a careful analysis of a particular design based on Edlund and Rhode's proposal would show to what extent the reactor history is essential for satisfactory control.

Maritime reactors may require exceptional reliability and ingenuity

Maritime reactors require that power be modulated to meet changing demands of the propulsive system. Furthermore, the maritime nuclear power system has three distinct response times or time constants—those of the reactor itself, the propulsive unit and the coupling between these two. The over-all time constant depends on all three. It is essentially the time required for every part of the system to "see" a transient in any part. It is extremely difficult to force the turbine to respond faster than this over-all time constant.

Improved sensing and data handling will reduce the number of shutdowns

Much corrective action has to do with what is prescribed as necessary for component failures. If some one would design a nuclear power plant such that not much need be done immediately after a failure of at least a few components, there is not much question in the author's mind that this would be a strong competitor against most present and contemplated designs as the power reactor of the future. The extensive system of sensing instrumentation merely adds more components that can fail.

Automatic data-handling equipment that compares incoming information with what it should be and alarms or initiates corrective action when deviations are detected undoubtedly would be very useful so long as there are many variables that must be monitored by either the operator or the control system. Data-handling equipment doesn't solve the basic problem of reducing the amount of information required for a good control system, but can take some of the awkwardness out of the methods of handling information in large quantities.

Continuing efforts to improve instrument reliability will help control-system development. But it appears that real improvement lies in the design of a power plant for which drastic corrective action is prescribed for a failure of only a few critical components. Since a transient initiated in a part of the plant is eventually seen by all of the system, relatively few sensors will be required to detect many component failures that require only minor corrective action by the control system. Most of these sensors can be placed where there is no problem of accessibility. In such locations their maintenance need not require that the power plant be shut down.

Spectral Shift Control

Changing the ratio of D_2O to H_2O in the moderator can provide shim and perhaps operational control as well. Reactivity lifetimes are extended beyond 30,000 Mwd/ton and power distribution is flattened

By M. C. EDLUND and G. K. RHODE, *The Babcock & Wilcox Co., Lynchburg, Virginia*

THE CONTROL OF REACTIVITY in pressurized-water reactors by continuous adjustment of the D_2O-H_2O ratio* appears to offer significant advantages. First the reactivity lifetime for close-packed water cores can be extended beyond 30,000 Mwd/ton without sacrificing the conversion ratio. The flexibility gained in choice of fuel cycle and initial fuel loading permits cost optimization throughout the power-plant life. Since there are no control rods, the power distribution can be made more uniform. For instance, with nonuniform fuel loading the maximum-to-average power distribution can be reduced to 1.5–1.6.

Spectral-Shift Concept

Burnup data for low-enrichment UO_2 or UO_2-ThO_2 fuel clad in either zircaloy or stainless-steel tubing is encouraging enough to make us think of designing reactor cores with reactivity lifetimes in excess of 30,000 Mwd/ton.

Published designs of water-moderated internal-converter reactors fall far short of this goal because of the limitations imposed by conventional reactivity-control systems. Absorbing rods do not control enough reactivity—soluble poisons in the water introduce operational as well as safety problems that also limit the amount of controllable reactivity—and burnable poisons (such as boron) may not have the proper burnout characteristics to provide sufficient shim control. Moreover, to get fuel irradiations as large as 30,000 Mwd/ton all these methods require initial fuel loadings with excess Δk as large as 0.20 to 0.30. Since in these methods the extra neutrons are absorbed unproductively there is a loss of about 0.2 to 0.3 in the average conversion ratio.

We propose a method that promises to avoid these difficulties—the use of a variable mixture of light and heavy water as the moderator. At the beginning of operation with a new core the moderator contains a high fraction of heavy water. As the reactor operates, reactivity loss due to the fuel burnup and fission-product accumulation is compensated by gradually diluting the moderator with light water.

For close-packed water lattices (metal-to-water ratio 0.7–1.2) the reactivity increases when D_2O is diluted with H_2O, mainly because the resonance absorption in fertile material is reduced. Since the slowing-down power ($\xi\Sigma_s$) for D_2O is only 0.13 that of H_2O, the resonance absorption in fertile material can be halved by increasing the volume fraction of H_2O in the moderator from 40% to about 100%. The excess multiplication of the core is thus controlled principally by neutron absorptions in the fertile material and so there is no reduction in conversion ratio as with control methods using unproductive neutron capture.

Dilution of the D_2O moderator with H_2O in an internal converter causes an appreciable shift in the neutron spectrum. This gives rise to many effects that cause the change in effective multiplication constant. The principal ones are:

- Decrease in resonance absorption in both fertile material and fuel
- Increased neutron absorption in hydrogen and structural material
- Decreased neutron leakage
- Decrease in the proportion of epicadmium fissions

The resulting change in k_{eff} depends strongly on the reactor type and design. For example, in large natural-uranium D_2O reactors the moderator-to-fuel volume ratio is so large that change in moderator absorption is the major effect. Hence in these reactors k_{eff} will decrease as H_2O is added to the D_2O. However, in the close-packed lattice of a fairly large pressurized-water reactor, change in resonance absorption is the dominant effect and

* NUCLEONICS **15**, No. 8, 66 (1957)

TABLE 1—Spectral Shift for U^{235}-Th Fuel

Deuterium/ hydrogen (D/H)	*Slowing-down power, $\xi\Sigma_s$ (cm^{-1})*	*Thorium resonance-escape probability*	*Epicadmium/ total fissions*	η_{avg}	*Initial conversion ratio (incl. equil. Xe and Sm)*
4.0	0.15	0.45	0.28	1.97	0.80
1.5	0.23	0.60	0.15	2.01	0.82
0.667	0.32	0.69	0.12	2.02	0.82
0.25	0.40	0.74	0.11	2.03	0.81
0	0.49	0.78	0.09	2.04	0.81

k_{eff} will increase as H_2O is added to the moderator.

Practical Example

To illustrate the physics of spectral-shift control consider a pressurized-water reactor design with these specifications:

Core diameter	7.15 ft
Core height	8.0 ft
Volume fractions	
Moderator	0.47
Zircaloy	0.26
Fuel and fertile material	0.27
Average moderator temperature	500° F

The fuel element is a bundle of parallel-spaced 0.31-in.-dia 0.026-in.-wall zircaloy tubes containing pellets of either low-enrichment uranium oxide or a mixture of thorium oxide and highly enriched uranium oxide. The oxide density is assumed to be 8.5 gm/cm³ in both cases. The fuel elements are cooled by parallel flow of the D_2O-H_2O moderator mixture.

As the deuterium to hydrogen ratio (D/H) in the moderator is decreased, the slowing-down power increases and the resonance absorption in fertile material decreases (as shown for the U^{235}-Th fuel in Table 1). The critical mass of U^{235} decreases, leading to a smaller proportion of epicadmium fissions and an increase in the average number of fission neutrons released per neutron absorbed in fuel, η_{avg} (see Table 1).

The neutron losses per neutron absorbed in U^{235} are given in Fig. 1. As the volume fraction of D_2O is decreased from 75% to 0%, the increasing absorptions in hydrogen and zircaloy nearly balance the reduction in neutron leakage so that the conversion ratio (see Table 1) remains almost constant.

TABLE 2—Changes in D/H for Operational Control Steps

Core condition	Critical D/H: Start of life	Critical D/H: End of life
Cold critical (70° F)	5.25	2.42
Hot critical (500° F)		
Zero power	3.00	1.12
Full power	2.69	0.98
Equilibrium Xe and Sm	2.27	0.70

For D_2O concentration above 75% the conversion ratio drops because of an increasing proportion of epicadmium fissions.

The reactivity lifetime of the core depends on the D/H ratio at the beginning of operation and, hence, the initial fuel loading. The calculated D/H ratio required for criticality as a function of the operating time at full power [800 Mw(th)] measured in Mwd/ton of thorium is given in Fig. 2 for initial D/H ratios of 3/1 and 9/1. The corresponding reactivity lifetimes are 27,000 Mwd/ton and 55,000 Mwd/ton respectively. The average conversion ratios are 0.78 and 0.70. The rapid reduction of D/H ratio after startup is due to Xe and Sm poisoning effects.

With U^{238} as the fertile material the results are similar. The average conversion ratios are somewhat smaller since Pu^{239} has a smaller η_{avg} than U^{233} for the spectra in these reactors. The reactivity lifetimes are also somewhat shorter for a given initial value of D/H. For example, the reactivity life of a new core starting at D/H = 9 corresponds to an irradiation of 34,000 Mwd/ton of U^{233}. The average conversion ratio is 0.63.

In either case, the long reactivity lifetimes result from the large amount of excess fuel that can be controlled by spectral shift and the relatively high conversion ratios that can be maintained during the operating life of the reactor core.

Breeding ratios greater than 1 may result with recycling of the U^{233} and higher uranium isotopes produced in the thorium cycle for fuel irradiations as large as 10,000 Mwd/ton of Th. Depending on the cost of fabricating and handling the radioactive fuel, breeding may or may not be the most economic operation. However, spectral-shift control will permit considerable flexibility in selecting the optimum core life.

Operational Control

In principle, a reactor can be operated by varying the D_2O concentration in conjunction with a constant-average-coolant-temperature–variable-steam-pressure control system.

The change in D/H ratio required to make a new core go critical at 500° F and D/H = 3 is given in Table 2.

As fuel is consumed and the moderator diluted with light water, Δk_{eff}/Δ(D/H) increases and a smaller change in D/H is needed to meet the operating requirements. For example, a core near the end of life will require changes in D/H approximately equal to those shown in the third column of Table 2.

Except for the temperature defect the reactor can be maneuvered at any given time with relatively small changes in the fraction of heavy water. A small on-site heavy-water separation plant capable of changing the D/H ratio of 150,000 lb of water in the range

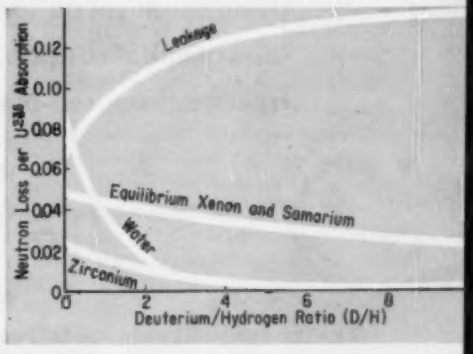


FIG. 1. Sources of neutron losses as a function of D_2O-H_2O ratio in the moderator

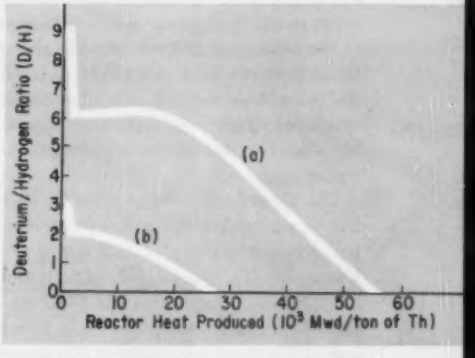


FIG. 2. Critical D/H vs. core burnup for pressurized-water core with: dia. = 7.15 ft; height = 8.0 ft; (total) fuel rod length = 246,000 ft; rod o.d. = 0.3125 in. Curve (a) is for initial U^{235} loading of 862 kg; average conversion ratio is 0.703. Curve (b) refers to 569-kg initial loading; average conversion ratio is 0.78

D/H = 0.2–6 at a rate of approximately 15%/day is adequate to meet the maneuvering requirements given in Table 2.

The heavy-water inventory for a 200,000-kw(e) power plant will be approximately 150,000 lb for a maximum volume fraction of 85% heavy water in the moderator at 70° F.

Fluid Poison Control of Boiling Water Reactors

Using chemical poisons such as boric acid rather than control rods promises lower capital cost, simpler maintenance, ready control of large reactivities, freedom from rod-placement problems and elimination of rod hot-spot factors

By **J. A. THIE**, *Argonne National Laboratory, Lemont, Illinois*

THE USE OF a fluid poison injected into the moderator is a common method of control in zero-power critical experiments but so far has been used in only a few power reactors. Because of the many reactor proposals involving the use of chemical control, it is worth discussing the experience accumulated to date on the use of this method in boiling-water reactors. This information presumably would be applicable to pressurized-water reactors.

The three boiling-water reactors that have used boric acid for reactivity control while running at rated power are Borax II (*1*), Borax III (*1, 2*) and EBWR (*3*). Boric acid (H_3BO_3) was chosen because tests showed it to be one of the more attractive of the possible fluid poisons with the following desirable characteristics: (a) high neutron-absorption cross section, (b) adequate solubility, (c) stability—it will not plate out, (d) low corrosiveness and (e) it is anionic—many cationic water impurities can be independently removed.

The advantages and disadvantages of chemical control have been discussed (*4, 5*) and are well known; however, its primary purpose in Borax II and EBWR was to assist in the understanding of boiling-water reactors. In Borax III, on the other hand, chemical control was required because the control rods lacked sufficient strength in the cold clean condition of that particular reactor.

Effects of Poison

The amount of reactivity held down by the acid varied, but typically was of the order of 3%. In the Borax reactors this amount generally did not appreciably affect performance because the water absorption was high and adding 3% to this was not a big change. In EBWR, however, water absorption changes from 10% to 13%, and this effect becomes amplified in the void coefficient (percent reactivity per percent coolant void) where the thermal-utilization effect is virtually canceled by the resonance-capture and leakage effects.

Self-terminating excursions in Borax II, with and without a few percent reactivity in boric acid, did not differ appreciably in peak power reached after a rapid control-rod ejection, which was as expected. When running any of the reactors at full power, the dilution/concentration effect is noticeable. A change in boric acid concentration, because of significant water-level variations, changes the reactivity available for compensation by steam voids and, hence, changes the power.

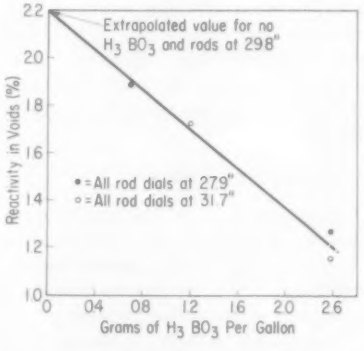


FIG. 1. Effect of boric acid addition on reactivity in voids of EBWR. Control rods also affect the reactivity held in voids as indicated by data for two rod positions

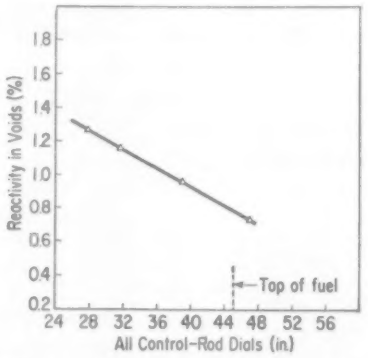


FIG. 2. Reactivity in voids of EBWR at power level of 19.62 Mw (pressure = 620 psig) with 2.373 gm of boric acid per gallon of coolant

The effect of boric acid on the void coefficient, and, hence, reactivity in voids, is quite noticeable in EBWR, as can be seen in Figs. 1 and 2. The control rods, which move in a bank down from the top of the reactor, also strongly influence the reactivity in voids at constant power because of two effects: (a) with control rods in, the reactor is effectively smaller and has a more negative void coefficient; (b) to generate the same power, the reactor, with control rods in, must run at a higher power density, and, hence, there are more voids in the effective core region than with control rods out.

By comparing then the influence of various concentrations of boric acid at the same power and rod position, its influences on the reactivity in voids can be seen. As expected, low acid concentrations mean more negative void coefficients.

Injection

Fluid poisons cannot normally be added as fast (in percent reactivity per second) as control rods, and a measure of the reactivity added is not always as simple. Steps in the addition are:

1. An accurately weighed amount of boric acid is dissolved in hot water.

2. The solution prepared is inserted into a special tank isolated from reactor pressure.

3. The tank's contents are injected into the reactor water, and the tank is flushed out. For EBWR at atmospheric pressure, and Borax at any pressure, gravity feed was used. For EBWR at operating pressure, the solution was inserted at the suction side of the feed pump.

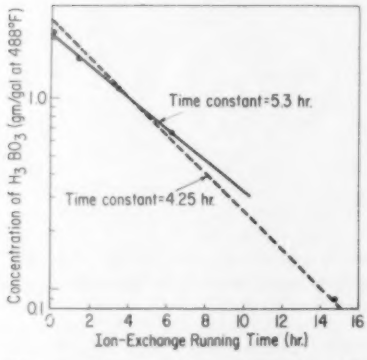


FIG. 3. Removal of boric acid with EBWR at power level of 20 Mw. Theoretical time constant is 4.25 hr divided by ion-exchange unit's efficiency

Reactivity Worth of Boric Acid

Reactor	*Temperature (°F)*	*Voids in coolant (%)*	*Reactivity per unit concentration H_3BO_3 (%/gm/gal)*	
			Theoretical	*Experimental*
Borax II	68	0	2.439	2.548
Borax III	68	0	2.339	2.366
EBWR	68	0	1.772	—
"	68	23.75	1.420	1.417
"	488	0	1.660	—

4. The reactor water is extensively circulated to insure thorough mixing.

Measurement

Because of our inexperience, we felt that several methods of determining the concentration in the reactor should be used simultaneously. Agreement has always been obtained among the following four methods.

Calculation. The amount of boric acid weighed out is divided into the reactor water volume, taking into account any removal by ion exchange or water dumping.

Titration. Mannitol (a hexatomic alcohol) is used to completely dissociate the acid into H^+ and $H_2BO_3^-$, and titration against NaOH proceeds in the usual fashion.

Neutron absorption. An apparatus was specially constructed (*2*) for determination of typically encountered reactor concentrations to very high precisions. The neutron-absorption apparatus contains a 5×10^7-n/sec Po-Be source that is 17 cm from a BF_3 counter. A sample of the reactor water flows through the apparatus. Comparison of a few minutes of counting with the counting of a standard solution can give 1.5% accuracy on a 0.005 *M* solution.

Control-rod motion. A change in the acid concentration can be followed directly by intercalibration of rod positions and concentrations, or indirectly by measured reactivity changes derived from rod positions and the theoretical reactivity worth of the acid.

The table shows agreement between the measured reactivity worth of boric acid (in terms of control-rod positions) and that calculated from reactor theory and the concentration determined by the first three methods. The existence of voids in the reactor water at room temperature is due to the presence of styrofoam for a separate void-coefficient measurement. One can infer a reactor's thermal utilization to have been accurately computed, from agreement of the type shown, since most of the absorption occurs in either water or fuel.

Removal

Complete water dumping is generally not possible in power reactors because of residual decay heat. Gradual dilution, ion exchange and removal in a special concentrating tank, therefore, offer practical, though slow, removal methods. Both dilution and ion exchange have been used and were found to obey, respectively, the simple dilution laws and the anticipated exponential decay

$$\frac{dM}{dV} = \left(\frac{dM}{dV}\right)_0 e^{-\frac{FE}{V}t}$$

where M is the boric acid mass in volume V, F is the flow rate and E is the column efficiency. Figure 3 shows the efficiency of a fresh ion-exchange column to be nearly 100%, as expected.

* * *

This work was made possible by the operating staffs of the Borax and EBWR reactors and, in particular, by C. B. Zitek, R. A. Mattson and R. E. Bailey.

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Control Rod Drives

Control-rod drives are as varied as the reactors they serve—from APPR's simple rack and pinion drive to VBWR's combination of pneumatic and mechanical elements. Here are some of them

By W. J. KANN and J. M. HARRER
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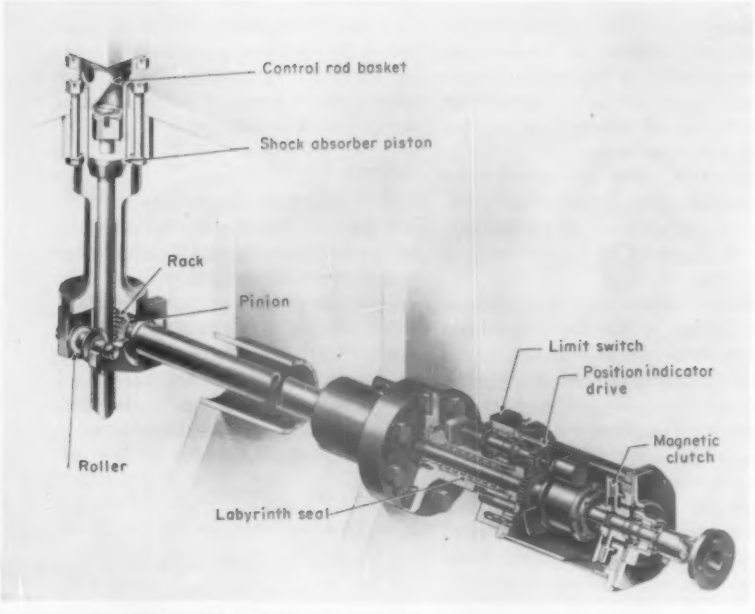
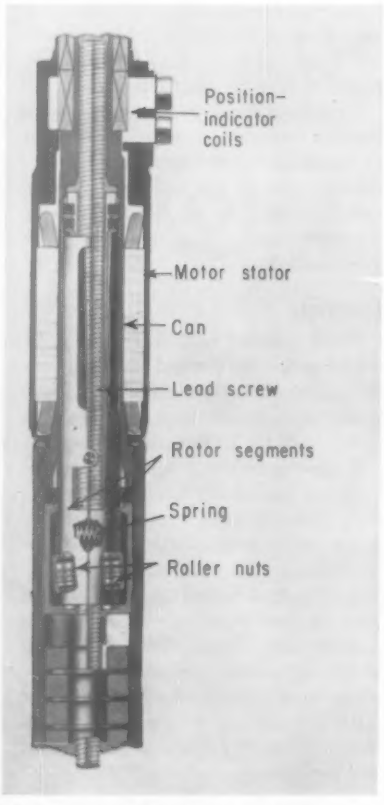


APPR-1 drives feature off-the-self components

Rack-and-pinion drives mounted underneath the pressure vessel move control rods of the Army Package Power Reactor. Commercially available three-phase induction motor provides the required power. Rack, pinion, pinion bearings and back-up roller operate in primary coolant (water). Pressure-breakdown, collected-leakage seal is used where pinion drive shaft penetrates the pressure vessel. Seal is basically the same as that used in EBWR except that the EBWR seal is used with a reciprocating shaft. Scram is initiated by de-energizing magnetic clutch. Position-indicator transmitter is driven by gearing connected to pinion extension shaft. Because gears are located on reactor side of magnetic clutch, continuous position indication is achieved. Control rods are pushed up out of the core to increase reactivity. Reactivity change-rate is about $2.6 \times 10^{-4}\ \Delta k/\text{sec}$.

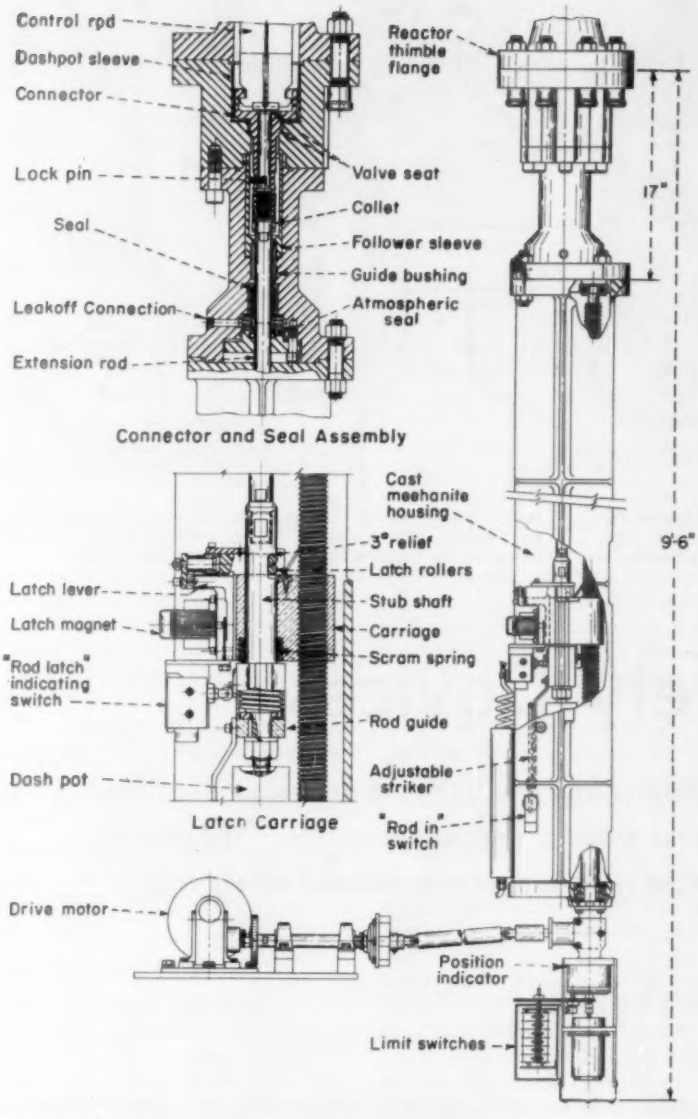
Comment. Dirt is less of a problem than in EBWR or PWR. With the present arrangement, the reactor must be shut down and drained to replace drive components that are in the primary coolant. This disadvantage could be overcome by placing these components in thimbles incorporating shut-off valves.



PWR stars collapsible rotor

Control-rod drives for the Shippingport reactor are mounted on the pressure-vessel head. Except for motor stator and position-indicator coils, all components are canned and subject to reactor environment. Lead screw is splined to control rod and driven by three-phase synchronous reluctance motor. To scram, rotor is de-energized, permitting spring to force it open and disengage roller nuts from lead screw, allowing rod to drop. Position indication is accomplished by differential-transformer coils located above motor.

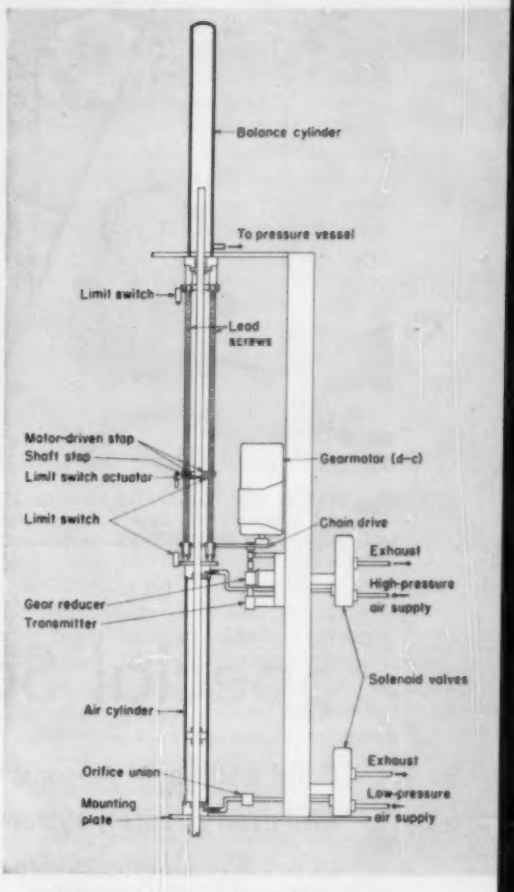
Comment. The components are inaccessible for routine maintenance, but operating experience has proved the drives very reliable. Complete reactor shutdown is required for drive repairs.



EBWR drives easily accessible for maintenance

Control-rod drive mechanisms for the Experimental Boiling Water Reactor are located below the pressure vessel. Extension shaft, operating through labyrinth-type pressure-breakdown seal, connects control rod to lead-screw with bayonet-type connector that has shutoff valve so that drive can be removed for maintenance without draining the pressure vessel. Lead-screw is driven through bevel gears connected to three-phase, induction gear motor. Reactivity-change rate is $6 \times 10^{-4}\ \Delta k$/sec. Secured to bottom of extension rod is lead-screw nut carriage having solenoid-and-spring operated scram latch. Reactor pressure is the primary stored-energy source; spring attached to extension rod serves only to overcome inertia at low pressures. Position indication is achieved by high-precision gear box and synchro transmitter-and-receiver pair.

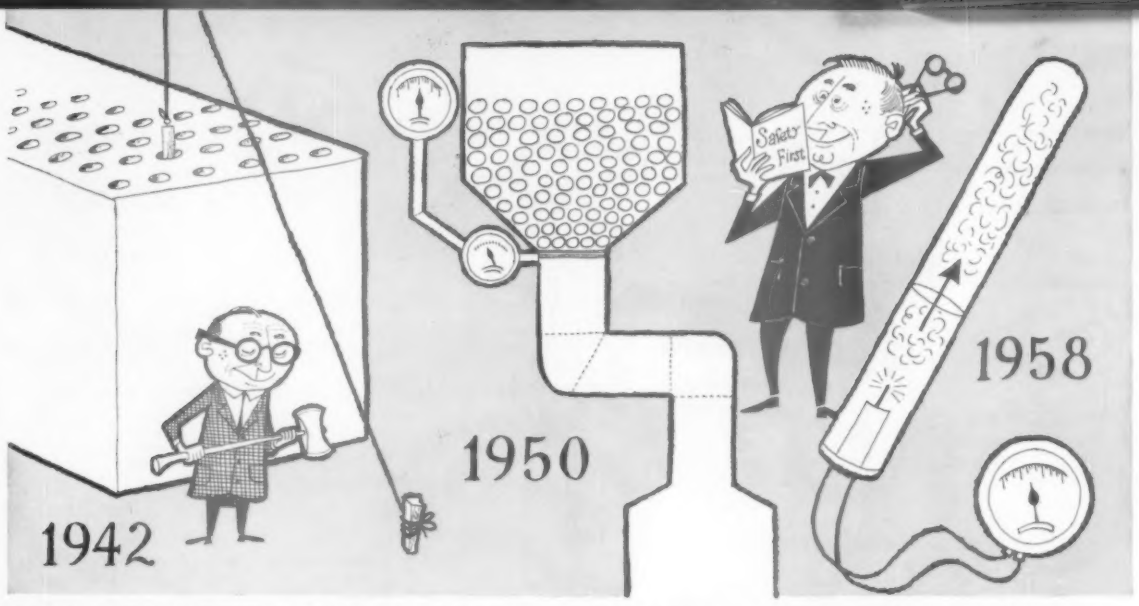
Comment. Dirt in the seal and extension-rod guide bushing has caused some operating difficulties at low pressures. The dirt causes the extension rod to bind, affecting scram time. Position indication after scram is not positive at all times because the synchro transmitter is coupled to the lead screw and not to the control rod. Indication again becomes positive only after relatching. Operating experience has shown that the external dashpot is entirely unnecessary and could be removed; this would reduce column forces on the extension rod.



VBWR uses pneumatic drives

Vallecitos Boiling Water Reactor drives are mounted above the pressure vessel. Double-acting air cylinder has one piston coupled directly to control rod and another coupled to balancing-cylinder piston. Balancing cylinder is connected to the reactor by steam line. Motor-driven stop traveling on lead screws is driven by d-c gear motor through chain-drive to determine control rod position. When limit switch mounted on motor-driven stop is in contact with stop on piston extension shaft, low-pressure air is introduced into lower end of cylinder to bring rod to desired position. Reactivity-change rate is $3.2 \times 10^{-4}\ \Delta k$/sec. To scram, high-pressure air is introduced into upper end of cylinder; air from lower end is exhausted. When motor-driven-stop limit switch loses contact with shaft stop, a signal is transmitted to gearmotor.

Comment. This type drive has an excellent service record; the Borax drive, after which the VBWR drive is patterned, has been in use since 1954. A more positive position-indicator than the synchro transmitter used would improve the drive; at present, the operator only knows where the motor-driven stop is located.



PROGRESS IN REACTOR SAFETY DEVICES: 1942—Norman Hilberry, axe in hand, ready upon oral scram signal to sever rope holding safety rod of CP-1; 1950—at Hanford, boron-steel balls held in hopper are automatically released upon signal into reactor thimble; 1958—integral device, independent of external power source, contains trigger, driving force and poison

Special Safety Devices

Solid and liquid poisons, moderator and fuel dumping are being considered and used as safety systems in the event of reactor excursions. The goal is to achieve simpler, more reliable systems than conventional safety rods

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CONVENTIONAL SAFETY SYSTEMS for nuclear reactors consist of a set of rigid absorber rods that are inserted into the reactor core upon the receipt of a scram signal supplied by electronic circuitry external to the reactor. However, such systems are usually complex and expensive and leave considerable room for improvement with respect to performance. Some of the out-of-the-ordinary safety devices conceived to supplement these standard systems are reviewed here.

Basic Safety Systems

There are four ways to shut down a reactor:

1. Increase parasitic absorption.
2. Increase neutron leakage.
3. Decrease moderation.
4. Decrease fuel content of core.

Most safety devices are of the first type. However, each of the other types has been used or proposed.

Safety devices can be categorized, too, according to the energy-storage mechanism—pneumatic, chemical, mechanical or gravitational.

The triggering of special safety devices can be initiated by a signal generated in the reactor-instrumentation system by any of several transducer and amplifier combinations.

Parasitic Absorption

If a safety device uses a parasitic absorber stored external to the core, it will have to be transported into a core (or possibly reflector) position subsequent to triggering. If stored internally, it can increase in effectiveness only by a change in geometry. In the second scheme, there is always a high stored-state reactivity loss.

Ball systems. Originally the third safety system at Hanford (backup in case the control and safety rods failed to function) operated by dumping a borax solution into the vertical safety-rod thimbles. This was replaced by a hopper-fed system that dumped boron-steel balls into the thimbles. Long response time is typical of such systems.

Liquid poisons. Liquid poisons are normally introduced into liquid moderators or into water coolant. Of course, the poison, once injected, must eventually be removed but this is no problem since a number of cadmium, boron, lithium and rare-earth salts can be effectively removed from aqueous moderators by ion-exchange resins (*1*).

Of the more promising solutes, only

borax appears suitable for power-reactor use (*2, 3*). The rare-earth salts require a high-acid environment to remain in solution and tend to form precipitates at high temperatures.

Liquid poisons appear to be too slow-acting for normal scram procedures. Rather, they have merit as the final backup system. An unusual application of such a system is found in the land-based Nautilus prototype. The high pressure of the coolant in this reactor presents a formidable obstacle to injection of a soluble poison. As a last-ditch precaution, a manual high-pressure pump was provided.

Leakage, Moderation Change

Motion of solid parts of the reflector has been used for safety purposes in several fast reactors. Typically, a block of the reflector material (natural uranium) is allowed to fall away from the bottom of the core (as in the Los Alamos Fast Reactor) or is driven downward pneumatically (as in ZEPHYR).

Rapid dumping of liquid moderator is provided for in several high-power reactors, including the CP-3, CP-5, NRX and NRU. This system is effective only because of the high moderating efficiency of heavy water—a relatively small change in level of the heavy water is sufficient to make the reactor subcritical.

Fuel-Content Decrease

The emergency discharge of fuel from the core can be brought about in two ways. Homogeneous liquid-fueled reactors such as HRE dump fuel solution into a storage tank. The same method may be applicable to liquid-metal-fueled reactors.

The second method provides that, if an incident should carry metal fuel elements to the melting point, the molten material would be dispersed into a noncritical geometry as it drops by gravity; this is to be the case in the Enrico Fermi Fast Breeder (*3, 4*). The fusible-link support for solid fuel elements, as used in ZEPHYR (*5*), has not been developed for power reactors because of conflicting requirements such as high creep strength at operating temperature, efficient cooling of link and quick operation.

Integral Safety Devices

"Integral" devices, being self-actuated and self-contained and thus independent of external linkage, either mechanical or electrical, are not subject to the ailments of the conventional safety-rod systems, such as power failures, circuit interruptions, stuck switches, incorrect wiring or operator errors. One would wish this device to remain operable in the reactor environment for at least one core life with little loss in sensitivity or change in trip level.

Since the neutron-absorbing material will likely be stored in or near the core, partial burnup of this material must be provided for. Furthermore, the device must be operable at least as well (preferably faster) when the reactor is cold as when it is hot, so as to guard against startup accidents.

The trip level should be preset to protect the reactor against an excessive neutron flux, rate of rise of neutron flux or temperature, or a combination of these. A typical trip level might be 50% above the normal neutron flux, or the lowest temperature in the reactor coolant that could prejudice the integrity of the fuel elements.

Thermal triggers. A simple thermal trigger consists of a thermal "pad" in contact with the reactor coolant and a fission-heat layer between the thermal "pad" and a solder layer.

During normal reactor operation, the heat generated in the fissionable material is drained through the "pad" to the reactor coolant; the thermal resistance of the "pad" keeps the temperature of the solder at a point perhaps one-third of the way between its melting point and the coolant temperature. In this case, increasing the neutron flux by 50% would melt the solder, triggering the safety device.

A trigger of this type (a) is sensitive to flux level and coolant temperature but only slightly to rate of change of flux, (b) therefore is much less sensitive to the cold or reactor-down conditioning, (c) has a considerable time constant because of thermal capacitance of its components—in practical cases, this turns out to be of the order of 1 sec, (d) can be made very rugged and reliable. If the thermal resistance of the pad could be made an inverse function of coolant temperature, the principal objection of point (b) would be removed.

A second type of thermal trigger is the "snap switch," which uses a bimetal strip of U^{238} and U^{235} that is sensitive to fission heat as a switch. The same criticisms apply here as in the first scheme. In addition, an electrical circuit is implied and, hence, a current source, which is difficult to maintain in a region near the core.

Pneumatic triggers. Pneumatic triggers use the expansion of a gas when heated by a fission process to rupture a diaphragm. They are severely sensitive to ambient temperature, unless compensated by a second chamber of gas not fission-heated. In high-temperature reactors, pressure containment might be a severe problem.

Poison-driving energy. Once the trigger has sensed an intolerable condition in the reactor, it must release stored energy to propel or relocate the neutron-absorbing material. This driving energy can be:

- Pneumatic. A compressed gas propels a poison, probably particulate, into a receiver chamber within the core or adjacent to it; alternatively the propelling gas itself may be a poison such as BF_3, arranged to become more effective upon redistributing itself. This may not be practical in sodium-graphite reactors though suitable in pressurized-water reactors.
- Chemical. A small explosive charge can be used to propel the poison or to rupture a diaphragm retaining a gaseous poison; this driver must be used in a low-temperature, low-radiation environment. A proposed system utilizes an exothermic reaction (e.g., boron exposed to fluorine) or a pyrophoric reaction (e.g., aluminum and oxygen triggered by a fission heater and used to volatilize a metallic poison).
- Mechanical or gravitational. These driving agents are not generally suited to integral safety devices because of slowness, high driving-energy requirements and possible jamming.

Only one truly integral safety device —in the sense that the trigger, driver and poison are completely contained in one capsule—that is possibly applicable to certain power reactors has been developed. A Ag-Sn eutectic solder plug is melted by a Cu-UO_2 heater to release a gaseous poison (*6*). It was originally developed for a relatively low-temperature, water-cooled reactor.

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Control Rod Materials

Materials technology is adequate for the needs of present reactor designs

Fabrication techniques for a variety of designs and materials are available

High cost and limited availability of materials present obstacles

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ON THE BASIS of the thermal-neutron-capture cross sections alone, there would appear to be many naturally occurring isotopes that would serve as control-rod materials. Furthermore, "tailor-made" combinations of elements for service in any given portion of the neutron-energy spectrum should be possible.

Performance criteria, however, rapidly reduce the list. Any reactor poison component must possess some measure of radiation-damage resistance, corrosion resistance, mechanical strength and metallurgical stability. In addition, the material must be fabricable and available in suitable quantities. These criteria were used in preparing Tables 1 and 2. All of the isotopes listed undergo (n,γ) reactions except B^{10}, which decays by (n,α).

Comparative costs for various types of fabricated control rods are given in Table 3. All rods are designed to meet service requirements in water-cooled, water-moderated reactor cores operating at 500–625° F.

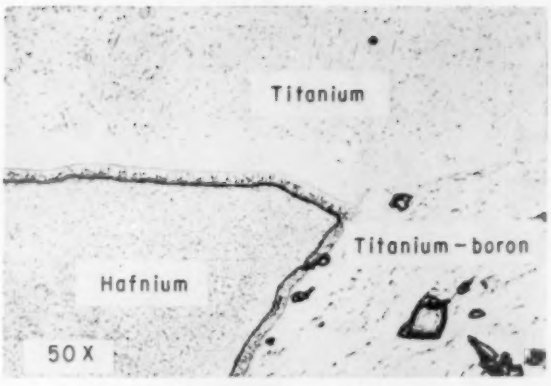
Properties of Materials

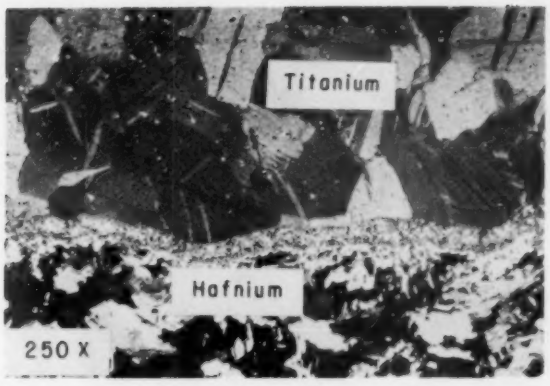
The mechanical and corrosion-resistance properties of unirradiated control materials are given in Tables 4 and 5. In general, the only materials considered satisfactory for water-cooled power reactors, other than hafnium, are stainless-steel-based systems, the other materials being applicable to specialized systems.

Table 5 compares some pertinent mechanical-property data in the unirradiated condition. In the case of the Cd-In-Ag alloys, improvement of the alloys is being actively pursued. The creep strength of the alloy is low at reactor-operating temperatures due to the low recrystallization temperature of the alloy.

Radiation damage is the most impor-

For these reactors . . .	These control rods . . .	Are suggested because . . .
Pressurized water	Hafnium or Eu_2O_3-ss	Only proven high-burnup control material—but relatively unavailable and expensive
Boiling water; high flux	Hafnium or Eu_2O_3-ss (clad)	Eu_2O_3, if in S.S. cermet and clad, provides high burnup without severe damage; each atom of 47.8%-abundant isotope Eu^{151} captures 5 neutrons; Gd_2O_3 can be substituted if only shutdown is required
Diphenyl coolant; long life	Eu_2O_3-ss (clad)	
Sodium-graphite; rods not removable	Eu_2O_3-ss AISI 347 clad	
CO_2, air or N_2 coolant; high temperature; high flux; rods not removable	Eu_2O_3-ss, clad	
Boiling water; rods replaced easily	Cd-In-Ag	Capture cross section comparable to Hf; radiation damage not excessive
Sodium-cooled, intermediate or fast reactor	Canned B_4C pellets	Excellent nuclear properties; expansion space needed for helium produced
Diphenyl coolant; short rod life	B^{10}-ss	Boron-steel is good for shutdown rods; radiation damage means short-lived control rods; B^{10}-S.S. and Cd-In-Ag seem to offer lowest-cost slab-type rods
Sodium-graphite; removable rods	B^{10}-ss	
CO_2, N_2 coolant; rods removable; medium temperature	B^{10}-ss	





POSSIBLE CONTROL MATERIALS. (Left) Titanium to titanium-boron dispersion to hafnium interfaces pack-rolled to 3-to-1 reduction at 1,600° F and flat-annealed at 1,400° F for 2 hr. (Right) Hafnium roll-clad with titanium at 1,600° F and air-cooled

tant criterion for selecting control materials. Of the materials listed in Table 3, the most data is available for boron and the rare earths.

Rare-earth studies. The radiation-damage resistance of rare-earth-oxide–stainless-steel dispersions has been studied primarily at KAPL. This work was done using bend tests. Relative ductility was determined from deflections at fracture or deflection at maximum load. The maximum load in a bend test on samples of the same size indicated the comparative strength of different materials.

The specimens used for this work were flat strips 0.050 in. thick, 0.200 in. wide and 3 in. long. They were mounted as simply supported beams and loaded in the center of a 1.5-in. span. Two to four specimens were irradiated in one capsule in the MTR.

Two specimens of Gd_2O_3–stainless-steel dispersions and four of Eu_2O_3–stainless-steel dispersions, fabricated by extruding compacted powders, were irradiated in the MTR in helium-filled capsules.

The Eu_2O_3–stainless-steel dispersions were irradiated in the MTR for two to five 17-day cycles. Table 6 gives the pertinent data. Considerable ductility is lost due to irradiation. Damage to areas adjacent to the Eu_2O_3 particles has been noted. The cause of this damage is not definitely known, although excessive internal temperatures (γ heating) may have caused an interaction with the silicon contained in the 302 stainless steel. However, the embrittlement during these irradiation tests would not rule out the use of Eu_2O_3–stainless-steel dispersions. Metallographic studies indicate that these networks do not connect up and no completely brittle tests were noted. No measurable growths were noted. Nevertheless, silicon-free alloys are recommended as matrix materials in Eu_2O_3 dispersions.

Cladding would add strength to the components and would provide a barrier between the reactor coolant and the hygroscopic Eu_2O_3 particles.

The 14 wt% Gd_2O_3–stainless-steel dispersions exhibited little damage after irradiation in the MTR for two cycles. Table 6 shows the good stability of this dispersion under irradiation. Growths in the order of 0.25% in width, 0.45% in thickness and 0.22% in length were noted.

Boron irradiation studies. The radiation-damage resistance of boron alloys and dispersions has been extensively investigated because of boron's excellent nuclear properties. The irradiation of boron alloys to any appreciable burnup, i.e., in excess of 0.5 total atom percent burnup, produces appreciable growth and drastically embrittles the materials. Table 7 indicates that the stainless-steel–boron alloys are the most promising if reasonable burnups are allowable.

Boron dispersions in titanium are the most promising from a damage

Another Viewpoint on Rare-Earth Absorbers

Although europium is the most effective neutron absorber of the rare earths, it is also the most expensive. Prices ($/lb) quoted by one supplier for 100-lb lots (>99% purity) are: Dy_2O_3, $115; Er_2O_3, $115; Sm_2O_3, $45; Gd_2O_3, $90; Eu_2O_3, $900. Costs might be reduced by at least partially replacing Eu in control rods with more abundant rare earths.

Small military reactors can tolerate high-cost control materials (e.g., APPR requires ~10 kg—$20,000 worth—of Eu_2O_3). However, in unenriched, lower-flux reactors, control-rod area may be 160–1,000 ft². Noncontinuous absorbers (e.g., Gd at ~$100/ft²) could satisfy long life requirements instead of Eu at $1,500/ft². In a large core, the cost difference would amount to between $200,000 and over $1,000,000 per set of control rods.

HIGH-FLUX REACTORS. For long-lived control rods, a rule might be to incorporate as much dysprosium, rather than Eu, as structure and nuclear-worth requirements permits. A 300-mil-thick stainless-steel matrix containing 1.4 gm/cm² Dy_2O_3 and 0.4 gm/cm² Eu_2O_3 would perform comparably to 0.9 gm/cm² Eu_2O_3.

MODERATE-FLUX REACTORS. In a 10^{13}-n/cm²/sec flux, where long rod life is less of a problem, gadolinium might be considered. However, to achieve a sizeable epithermal cross section, Gd would have to be used in conjunction with Er, Sm, Eu and/or Dy.

"SANDWICH" TECHNIQUES. If one poison is shielded by another, it is possible to attain longer rod life than if the poisons were mixed homogeneously. For example, if all the Eu were in the center of the rod surrounded by Dy, the slower-burnout Dy would serve as a shield for the more rapidly burnable Eu. By this technique, the life of a resonance absorber can be extended.—*Based on material submitted to* NUCLEONICS *by* J. A. RANSOHOFF, *Washington, D. C.*

standpoint. Considerable ductility is retained in the material through the integrity of the matrix material. However, the growth of the boron dispersions is concentrated in small areas. This would require cladding to prevent the boron from contaminating the coolant.

Normal boron carbide has been irradiated in the following systems: B_4C dispersed in Al_2O_3, B_4C in Zr, B_4C powders and hot-pressed B_4C compacts. In general, the irradiation data indicate that expansion space must be provided to contain the helium released. However, the minimum amount of expansion space that must be provided to contain the released helium cannot be accurately predicted. In one case, 2.2 wt% B_4C-Al_2O_3 (82% density) released 1.4% of the helium at 93% burnup. In another study, hot-pressed B_4C during 16.6% burnup in a sodium-vacuum environment at 600° F for 45 days released 2.6% of the helium. Up to 10% was released from vibrating B_4C taken to 5% burnup in a helium environment at 270° F for 104 days.

In sodium-cooled reactors, B_4C control rods have performed satisfactorily. These rods contain powders or hot-pressed pellets. Both types of rods are headered to a collection tank large enough to contain all the helium theoretically generated. Because of the low release rate of helium from B_4C, these designs are conservative.

The only fully proven long-life, high-burnup control material from a radiation-damage standpoint is hafnium. Hafnium control rods were successfully used for a full core life in the Nautilus reactor.

Some preliminary radiation-damage studies have been made of silver alloys. Data is not available, but the damage is not excessive for short-term irradiations. This alloy system may be promising.

TABLE 2—Nuclear Properties of Control Poisons

Isotope	*Abundance (%)*	σ_a *(barns)*	*Remarks*
B^{10}	18.9	4,000	Isotopic enrichment desirable
Hf^{176}	5.2	30	Must be used as
Hf^{177}	18.5	370	massive slabs
Hf^{178}	27.1	80	
Hf^{179}	13.8	65	
Hf^{180}	35.2	10	
Eu^{151}	47.8	9,000	Equivalent to
Eu^{152}		5,000	massive Hf at
Eu^{153}	52.2	420	20 vol. % con-
Eu^{154}		1,500	centration
Eu^{155}		13,000	
Gd^{155}	14.7	70,000	Too high cross
Gd^{157}	15.7	180,000	section; very fast burnout
Sm^{149}	13.8	66,000	Of little interest
Ag^{107}	51.4	30	Rather low cross
Ag^{109}	48.6	84	section
Cd^{113}	12.3	27,000	Sharp cutoff in epithermal range
In^{113}	4.2	63	Good in epither-
In^{115}	95.8	197	mal range

TABLE 3—Estimated Cost per Rod for Manufacture of Triflute Rods

Type of rod	*Tooling*	*Material*	*Fabrication (includes profit)*	*Inspection and packing*	*Total*
Welded Hf rod	$500	$4,460	$6,000	$2,000	$ 7,900
Extruded Cd-In-Ag rods	500	2,080	4,000	1,500	6,250
Extruded or hot-rolled and welded Eu_2O_3-cermet rod (AISI 304 steel matrix)	500	6,100	4,400	1,000	12,000
Composite rod with Ti-clad blades with 14 in. Hf and 16 in. 3.5 wt% B^{10}-Ti dispersion	500	6,300	9,300	1,000	14,200
Welded stainless-steel–boron rod	500	2,975	3,750	500	5,700
Extruded or hot-rolled and welded Ti-Eu_2O_3, Ti-clad composite rod	500	4,730	4,400	1,000	10,630

Fabrication

Frequently reactor-design criteria dictate the selection of control material. For example, the use of very high-cross-section nonmetallic materials such as Eu_2O_3 may be dictated by the range of neutron energies.

In such instances, dilution of the poison is necessary, usually by dispersion in a metallic matrix. Since these dispersions lack corrosion resistance to high-temperature water, they are usually clad.

When stable, fabricable alloys of the poison material are available, alloying seems advisable for absorber dilution. Alloys are generally less expensive than powder-metallurgy dispersions, usually meet chemical-homogeneity specifications better and often exhibit better corrosion properties. Zr-B, Ti-B and austenitic stainless-steel-boron have been investigated as control materials. The last has found widest application because it is readily fabricable and the most corrosion resistant, being usable without cladding.

Boron control rods. To achieve maximum metallurgical stability, it is desirable that control-rod alloys be single-phased at operating temperatures. For example, the addition of boron to AISI type 304L is usually accompanied by an increase in nickel content to 12–15 wt% for complete austenitization. The boron is preferably <1.5 wt% so that excessive scrap losses (due to hot shortness) are kept to a minimum in subsequent hot-rolling operations. Thus, it is necessary to enrich the boron in B^{10} in some cases to provide nuclear blackness throughout core life. To conserve B^{10}, vacuum melting of enriched alloys is often employed.

Multibladed stainless-steel–boron alloy control rods are prepared by welding together hot-rolled (1,050–1,150° C) and cold-finished alloy plates of appropriate thickness. Depending on the design of the jig employed, subsequent straightening operations may or may not be required. A stress-relief annealing treatment is always employed after straightening, and finish-machining operations are used to adjust the blade span and the "wear pads" at the bottom end of the rod.

Hafnium rods. Hafnium-control-rod fabrication is similar to that just described.

TABLE 4—Preirradiation Corrosion Resistance of Control Materials*

Material	*Water (600° F)*			*Diphenyl (750° F)*	*Sodium (1,100° F)*	*Helium (1,500° F)†*	*Air (1,500° F)†*	*Nitrogen (1,500° F)†*	*CO_2 (1,500° F)†*
	Degassed	*Hydrogenated*	*Oxygenated*						
Hafnium	✓	✓	✓		✓	✓			
18-15 ss–<1 wt% B	✓	✓	✓	✓	✓	✓	✓	✓	✓
AISI 304–<1.5 wt% B	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ti-B alloys to 1.5 wt% B^{10}	✓	✓	✓		✓	✓			
Ti-B dispersions to 3.5 wt% B	✓	✓	✓		✓‡	✓			
Zr-B alloys to 1 wt% B	✓				✓‡	✓			
5 wt% Cd-15 wt% In-80 wt% Ag	✓	✓							
30 wt% Cd-70 wt% Ag									
B_4C (hot-pressed, sintered)				✓	✓	✓		✓	✓
Rare-earth-oxide ceramics (Gd_2O_3, Linsay Mix)						✓	✓	✓	
Rare-earth-oxide cermets									
35 vol% Eu_2O_3-AISI 302B				✓	✓§	✓	✓	✓	✓
20 vol% Eu_2O_3-AISI 302B				✓	✓§	✓	✓	✓	✓
15 vol% Eu_2O_3-AISI 302B				✓	✓§	✓	✓	✓	✓
15 vol% Sm_2O_3-AISI 302B				✓	✓§	✓	✓	✓	✓
15 vol% Sm_2O_3-sponge Ti				✓	✓§	✓	✓	✓	✓

* Checks indicate good corrosion resistance.
† Estimate by author.
‡ With low oxygen.
§ Based on similarity to ss-UO_2 dispersions at KAPL. Also see "Behavior of Materials in Non-Aggressive Liquid Metals," Special Report No. 2, E. G. Brush and R. F. Koenig, Feb. 20, 1956.

TABLE 5—Preirradiation Mechanical Properties of Some Control Materials

*Alloy**	*Yield strength, 0.2% offset (psi)*	*Ultimate tensile (psi)*	*Elongation (%)*	*Reduction in area (%)*	*Modulus of elasticity × 10^6*
Stainless Steels					
0.5 wt% B^{10}-18 Cr-15 Ni-ss	29,000	81,000	29.6		
0.5 wt% B^{10}-18 Cr-15 Ni-ss	23,000	62,000	19.8		
0.85 wt% B^{10}-18 Cr-15 Ni-ss	33,000	85,000	21.1		
Boron-Titanium					
0.29 wt% B^{10}-Ti	89,300	102,200	22	46	15.5
0.62 wt% B^{10}-Ti	83,300	102,400	18	39	16.5
0.62 wt% B^{10}-Ti	90,400	101,000	14	40	17.8
1.10 wt% B^{10}-Ti	96,700	108,300	18	33	16.5
1.7 wt% B^{10}-Ti	94,700	111,800	6	14	16.5
Boron-Zirconium					
0.4 wt% B-Zr	40,000	65,900	20	36	
0.4 wt% B-Zr	43,800	68,000	16	39	
0.8 wt% B-Zr	61,500	90,300	13	29	
14 wt% B-Zr	55,600	83,600	13	25	
Other					
5 wt% Cd-15 wt% In-80 wt% Ag	10,000	43,000	54	71	
Hafnium	30,000	55,000	18	23	

* All alloys annealed except 0.62 wt% B^{10}-Ti and 0.4 wt% B-Zr, which were hot-rolled. All were tested at room temperature except 0.5 wt% B^{10}-18 Cr-15 Ni-ss, which was tested at 600° F.

Sponge hafnium is converted to crystal bar by the iodide process, arc-melted, remelted by a vacuum arc-melting, forged, conditioned and hot-rolled (975° C) into plate. Plate thickness is controlled to ±0.002 in. in a final cold-rolling pass, which also provides a good surface finish. The hafnium plates are then trimmed, machined and butt-welded to shorter plates of Zircaloy-2 in a welding box under an extremely pure helium atmosphere. These composite plates are then flat-annealed and assembled with a Zircaloy hub (Fig. 2). Final joining of rods is accomplished by fusion welding in a pure helium atmosphere at 180 amperes, 16 volts, d-c.

It should be noted that single-phase alloy joints are produced when hafnium is fusion-welded to Zircaloy because these materials form a continuous series of solid solutions when alloyed. The metallurgical stability of the assembly is, therefore, not appreciably less than that of either material separately under reactor conditions.

Other materials. The hafnium fabrication procedure has also been applied, with modifications, to the production of (a) titanium-clad, Ti–3.5% B^{10} dispersions; (b) stainless-steel-clad, stainless-steel–rare-earth dispersions; and (c) composite control rods. All of these, clad for protection against corrosion, involve "picture-frame" rolling techniques. The picture-frame pack is fusion-welded together, evacuated and sealed off before hot rolling. Complete metallurgical bonding is realized with cross-sectional-area reductions as small as three to one at 850° C in the case of Ti–3.5% B^{10}, titanium-clad plates, for example. Larger (15 to 1) reductions are used for stainless-steel-based plates.

Dispersion core materials used in either composite or rare-earth-oxide control rods are prepared for rolling by particle-sizing the poison, blending the poison and the matrix metal, cold pressing and finally sintering. Titanium- and zirconium-based dispersions are sintered under vacuum whereas stainless-steel-based dispersions can be sintered in hydrogen to reduce the iron oxides present. They are then machined to size and placed in the picture-frame-rolling assembly.

The composite control rod was conceived as a method of hafnium conservation. Since only the lower portions of control rods are exposed to

TABLE 6—Bend-Test Results before and after Irradiation*

Absorber (in stainless)	*No. of MTR cycles†*	*Max. load*	*Deflection at max. load*	*Deflection at fracture*	*Ductility index‡*
5 wt% Eu_2O_3	Unirradiated	19	0.300	None	
	2	36	0.175	None	0.583
20 wt% Eu_2O_3	Unirradiated	17	0.320	None	
	5	32	0.100	0.100	0.312
25 wt% Eu_2O_3	Unirradiated	16	0.300	0.370	
	5	27	0.100	0.100	0.333
30 wt% Eu_2O_3	Unirradiated	15	0.270	0.550	
	3	21	0.090	0.090	0.333
14 wt% Gd_2O_3	Unirradiated	26	0.250	None	
	2	40	0.225	None	0.900
14 wt% Gd_2O_3	Unirradiated	26	0.380	None	
	2	35	0.350	None	0.921

* Eu_2O_3 tests conducted at room temperature, Gd_2O_3 tests at 600° F.
† MTR cycle is 15 days, in these instances at fluxes of $2.0–2.5 \times 10^{14}$ nv.
‡ Ductility index is defined for bend specimens as the ratio of the irradiated deflection at maximum load to the unirradiated deflection at maximum load.

high neutron flux for extended times, the upper sections of control rods can be made of materials less resistant to radiation damage. The rod is, therefore, composed of a control section, a shutdown section and a hub to which the drive mechanism is attached. Composite plates have been made with both blade sections titanium-clad, the shutdown-section meat material being hafnium and the control section being a Ti–3.5 wt% B^{10} dispersion, which is designed to receive less than 1% burnup of the total core material atoms present. The hafnium must meet only nuclear-worth, irradiation-damage and strength requirements; its corrosion resistance may be substandard because it is clad.

Tubular AISI-347 steel cans, filled with dense B_4C compacts or other ceramic materials, are fabricated by straightforward assembly techniques. For boron-containing ceramics, vent tubes are attached at the top of each can to lead the helium produced by neutron bombardment of B^{10} into a suitably designed reservoir. Such gas-collection systems would not be necessary for canned rare-earth ceramics.

Extrusion. Extrusion has also been used for fabricating control components. At present this technique is applied only to relatively soft, unclad materials. This is principally because the semifinished cross-sectional areas of control rods are usually small in comparison with those of the extrusion billets. As long as this is true, stainless-steel rods, for example, will not be extruded because the required tonnages cannot be supported by the tooling. Unclad alloys were specified because of the nonuniform final claddings realized when multibladed rods are extruded from round starting billets.

When control rods require materials that cannot be fabricated by conventional techniques, both the cladding-uniformity problem and the extrusion-pressure difficulty can be avoided by a rather unorthodox extrusion method. A shortened, enlarged control rod is mounted in an extrusion billet of round cross section and extruded through a round die at low reductions. The billet, composed mostly of a relatively soft filler material, requires low extrusion pressures, and since the reduction is the same at all points in the blade cross section, a uniform cladding layer results. The extruded rod is removed from the center of the round extruded shape by machining and dissolution of the billet envelope. This technique is expensive but can be used to make control rods containing a large proportion of brittle, dispersed phase.

Hot extrusion has been recently applied to the fabrication of 80% Ag–15% In–5% Cd control rods. This alloy has a single-phase face-centered-cubic structure and was chosen because it has moderately good corrosion resistance to 600° F water and neutron-absorption characteristics much like those of hafnium. Cast alloy is extruded at 1,000° F.

* * *

TABLE 7—Effect of Irradiation on Boron Alloys*

Material	*Integrated flux (10^{20} n/cm²)*		*Ductility index†*
	Thermal	*Fast*	
0.56 wt% B^{10} in Ti	2	0.2	0.478
0.21 wt% B^{10} in Zircaloy-2	10	1	0.500
18–15 ss–0.5-wt% B^{10}	3	0.3	0.155
18–15 ss–0.85-wt% B^{10}	10	1	0.042
18–15 ss–0.19-wt% B^{10}	10	1	0.700
AISI ss	3	0.6	0.980

* Tests made at room temperature.
† Ductility index is defined for bend specimens as the ratio of the irradiated deflection at maximum load to the unirradiated deflection at maximum load.

This article is based on the following papers presented at the Symposium on Reactor Control Materials conducted as part of the Second Winter Meeting of the American Nuclear Society, October, 1957 (unless otherwise noted, authors are members of the staff of Knolls Atomic Power Laboratory):

Kermit Anderson, "Broad Aspects of Absorber Materials Selection for Reactor Control"

D. N. Dunning, Kermit Anderson, "Rare Earth Cermets under Radiation"

L. B. Prus, E. S. Byron, J. F. Thompson (Westinghouse Electric Corp., Bettis Plant), "Boron Stainless Steel Alloy Control Rods"

D. N. Dunning, Kermit Anderson, "Boron Containing Control Materials"

W. E. Ray, C. J. Beck, "A Method of Hot Coextruding Complex Shapes through Round Dies"

J. Giacobbe (Superior Tube Co.), D. N. Dunning, "New Developments in the Fabrication of Hafnium Control Rods"

W. E. Ray, H. W. Cooper (Superior Tube Co.), W. A. Neisz, "Discrete Fixed Poison Rods Containing Boron"

S. J. Paprocki (Battelle Memorial Institute), W. E. Ray, D. Keller (BMI), "Feasibility of Composite Slabs for Reactor Control Applications"

W. E. Seymour, W. Barney, "The Use of B_4C for the Control of Sodium Cooled Reactors"

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Scintillation-Counter Analysis of EBWR Radioactivity

By S. J. GOSLOVICH, J. H. PINGEL and H. R. FISH
Industrial Hygiene and Safety Division, Argonne National Laboratory, Lemont, Illinois

The Experimental Boiling Water Reactor (EBWR) startup occurred on December 23, 1956, and the reactor reached its rated 20,000-kw power level on December 28. During full-power runs in early January, 1957, radiation safety personnel noted abnormally high air activity inside the EBWR shell. Filter paper taken from an air sampler was analyzed. It showed particulate Cs^{138} activity, presumably from the decay of its noble-gas parent, Xe^{138}, which has a half-life of 17 min. Assuming equilibrium conditions, the Cs^{138} air concentration was determined to be $\sim 1.2 \times 10^{-7}$ $\mu c/cm^3$ at the time of sampling.

A systematic study of various reactor media was begun. Air-ejector gas, condensed steam and reactor-water samples were analyzed in bulk form by scintillation-counting methods. Tables 1 and 2 summarize the activities that have been identified to date. Also listed in the tables is the ratio of concentration to maximum permissible concentration (MPC) (*1*) for those isotopes present in sufficient quantity. All activity levels were determined after the reactor had operated at 20 Mw for at least 24 hr.

It is evident that those gamma-emitting radioisotopes that have been present in the EBWR environment during the past year (1957) did not greatly exceed the MPC. While the Cs^{138} concentration at the air ejector has been about 150 times MPC, this concentration is greatly reduced when the air-ejector gases are diluted with room air in the exhaust duct.

The longest-lived isotope that has been detected at EBWR is Co^{60}. Its presence has been determined by analysis of filter materials and mixed-bed resins that are located in the water-purification loop. However, after about eleven months of intermittent reactor operation, the Co^{60} concentration in the mixed-bed resin column has been insufficient to enable a quantitative determination. Presumably, the Co^{60} generation is due to the (n,γ) reaction with natural cobalt, which is present in small amounts (<1%) in most stainless steels. Therefore, cobalt-bearing materials should be avoided in the structural components of future boiling-water reactors.

Water and Steam Activity

The water and steam samples listed in Table 1 were analyzed as large-volume sources. Geometry was estimated by assuming that a large-volume source could be represented by an equivalent point source located at its center of mass. The condenser-tubing sample had a mass of only 33 mg and, therefore, was considered a point source.

The presence of 72-day Co^{58} was determined by following the decay of its 810-kev line for about 45 days. The decay curve indicated a half-life of about 76 days.

Another radioisotope present in EBWR water and steam is F^{18}. Since this positron emitter does not emit gamma radiation, its associated 510-kev annihilation quanta provide the sole means of detection by gamma-scintillation counting. However, F^{18} activity is easily confused with that of Co^{61}, since their half-lives differ only by 10% and Co^{61} emits a "true" 510-kev gamma-ray. Thus, a chemical separation must be carried out. According to Table 1, the decontamination factor (ratio of water to condensed-steam activity) for F^{18} is only 4.33. Presumably, most of the F^{18} is carried over as HF.

Gas Activity

The gas passing through the EBWR air ejector consists primarily of H_2 and O_2 and normal room air, which leaks into the system at the turbine and the condenser. The H_2 and O_2, originating from H_2O disassociation, are swept from the reactor by steam to the tur-

TABLE 1—Neutron-Induced Activities at EBWR

Isotope	*Half-life*	*Gamma-rays (Mev)*	*Probable formation*	*Concentration* ($\times 10^{-2}$ $\mu c/cm^3$)*	*Conc./MPC*
Reactor water					
Mn^{56}	2.6 h	0.850	Fe^{56} (n,p)	4.5	0.3
		1.82	Mn^{55} (n,γ)		
		2.15			
Na^{24}	15 h	1.36	Al^{27} (n,α)	1.5	1.9
		2.75	Na^{23} (n,γ)		
Co^{58}	72 d	0.81	Ni^{58} (n,p)	0.088	0.04
Co^{60}	5.2 y	1.17	Co^{59} (n,γ)	Trace	≪MPC
		1.33	Ni^{60} (n,p)		
F^{18}	1.9 h	0.51†	O^{18} (p,n)	1.3	0.01
Condenser-tubing deposit					
Co^{58}	72 d	0.81	Ni^{58} (n,p)	8.8	
Reactor steam‡					
F^{18}	1.9 h	0.51†	O^{18} (p,n)	0.3	
Co^{58}	72 d	0.81	Ni^{58} (n,p)	Trace	
Anion resin					
Cr^{51}	26 d	0.32	Cr^{50} (n,γ)	?	

* All concentrations determined for 20-Mw reactor operation over periods of 24 hr or longer.
† Annihilation quanta.
‡ The steam samples were taken at a point before the steam enters the steam dryer. The concentration is given per cm^3 of condensed steam.

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Write for Bulletin No. 161

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This article starts on page 94

bine and condenser. From the condenser, the gases flow through the air ejector and then to a holdup tank. The gas flow from the reactor to holdup tank takes about 1 min.

Since the gases are concentrated at the air ejector, it is a logical sampling point. Samples were obtained in a 1-liter, stainless-steel chamber with 4-mil-thick windows. The chamber was partially evacuated, and then air-ejector gases were flushed through the chamber for several seconds. Table 2 lists the fission products that have been identified in these gases.

A cotton filter was inserted in the line ahead of the sample chamber to trap any particulate matter. Scintillation analysis of the filter indicated the presence of Ba^{139} (Table 2). Since the sample was analyzed about an hour after it was obtained, most of the 10-min Cs^{139} activity had decayed leaving the Ba^{139} daughter. Unfortunately, there was not enough Ba^{139} to calculate its concentration.

The same situation, i.e., a short-lived parent decaying into a longer-lived daughter, prevailed in the case of Cs^{138}. Very little Xe^{138} was observed because of the lapse of time between collection and analysis.

All activities listed in Table 2 result from xenon and krypton, two high-yield, gaseous fission products. Apparently these gases escape through the Zircaloy cladding by diffusion and enter the reactor water and steam. The presence of a relatively large break or rupture in a fuel element must be discounted since no other fission products have been observed. Iodine activity, for instance, is always observed in a fission-product release involving exposed fuel (*2, 3*). On the same basis, it can be assumed that no appreciable uranium contamination exists on the outside of EBWR fuel elements.

Equipment

Measurements and analyses of EBWR activity were made using single channel analyzer equipment, a 5-in. photomultiplier tube and a 4 × 4-in. NaI crystal.

The electronic equipment consisted of a linear amplifier, a single-channel pulse-height analyzer, an electronic sweep circuit for automatically scanning any portion of a 0–100-volt pulse spectrum, a counting-rate meter, a scaler, a variable 500–1,000-volt high-voltage supply and a Brown strip-chart recorder.

A cylindrical 4 × 4-in. NaI crystal was "canned" by Electronics Div. personnel in a 5-mil aluminum can and then sealed with Apiezon-Q sealing compound directly to a 5-in. Du Mont photomultiplier tube. To date, there is no evidence of deteriorating resolution due to moisture absorption by the crystal. Improved photopeak resolution was obtained by optimizing the photomultiplier cathode-to-shield and shield-to-first-dynode voltages. As a result, resolution for the Cs^{137} line is 8.5–9.0%.

Shielding for the crystal, photomultiplier and preamplifier consists of 4 in. of lead brick and 2 in. of iron plate. The material forms a "cave" with inside dimensions of 10 × 10 × 24 in.

TABLE 2—Fission-Product Activities at EBWR

Isotope	*Half-life*	*γ-rays (Mev)*	*Decay chain*	*Concentration (μc/cm³)*	*Concentration / MPC*
Air-ejector gas					
Cs^{138}	33 m	0.46 0.98 1.44	$Xe^{138} \rightarrow Cs^{138}$	7.4×10^{-3}	150
Xe^{135}	9.2 h	0.250	$Xe^{135m} \rightarrow Xe^{135}$	3.2×10^{-4}	0.32
Kr^{85m}	4.5 h	0.150	U fission	1.2×10^{-4}	
Air-ejector filter					
Ba^{139}	85 m	0.163	$Xe^{139} \rightarrow Cs^{139} \rightarrow Ba^{139}$	Trace	
Ion-exchange filter					
Ba^{140}-La^{140}	13 d	1.60 2.55	$Xe^{140} \rightarrow Cs^{140} \rightarrow Ba^{140} \rightarrow La^{140}$	Trace	
Room air					
Cs^{138}				1.2×10^{-7}	0.002

Decay-Rate Determinations

In these measurements, the beta-ray disintegration rate of a beta-gamma source is expressed by $D = c/eribg$ where D = beta disintegration rate in dpm, c = net counting rate under the photopeak in cpm, e = intrinsic efficiency of the crystal for any type of gamma interaction, r = the ratio of area under the photopeak to total counting area under the curve, i = internal-conversion factor, b = gamma-branching factor and g = geometry.

The factors i and b are easily obtained from compilations of nuclear data. The geometry g has been determined in all cases as that resulting from a point source symmetrically located at a height h above the crystal. For the 4-in.-diameter by 4-in.-high crystal, the geometry factor is

$$g = \frac{1}{2}\left[1 - \frac{h}{(h^2 + 4)^{1/2}}\right]$$

where h is in inches.

The factors e and r are functions of gamma-ray energy and were determined for the particular type and size of crystal employed (*4*).

* * *

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Xenon-Poisoning Computer

By J. J. PAUL and J. R. G. COX
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Montreal, Canada

Xenon-135, a fission product with high thermal-neutron absorption cross section, necessitates large positive-reactivity changes to overcome its poisoning effect in high-flux reactors. The Xe^{135} may rise to such levels that the excess reactivity built into the reactor is insufficient to maintain criticality.

Numbers that are frequently required in reactor operation are the time for which the reactor can be shut down and still be started up in time to avoid poisoning out (i.e., reach a poison level that the reactor cannot override), and, if the reactor does poison out, how long it must remain shut down. Operating limits can be fixed for the simple case of startup and running at full power until Xe^{135} concentration reaches equilibrium. However, a research reactor may be started up and shut down repeatedly, making such calculations difficult. Also, it is not economical to build in enough excess reactivity to cope with peak Xe^{135} concentrations.

To meet this problem, a computer was built for use with the NRU reactor (Figs. 1 and 2). With the computer, the effect of any changes in reactor power on Xe^{135} concentration can be predicted and steps taken to avoid poisoning out. While the computer cost $16,000, it is estimated that a poison shutdown that keeps the NRU inoperative for 40 hr represents a loss of about $30,000.

The computer was designed for ~1% accuracy in Xe^{135}-concentration readings. Tests on the experimental model have shown that it is capable of better than this.

An electromechanical system was adopted for the computer to avoid the inherent disadvantages that electronic analog computers present for problems of very long solution times. Among the disadvantages are possible loss of stored information due to line-voltage failures or tube failure, surges and instantaneous insulation breakdown. Also, long time constants, which require extreme-value resistors and capacitors, may vary due to drift and leakage.

The electromechanical analog computer is free from these disadvantages. Its only limitation is the accuracy of the potentiometers and the servo system. Since the potentiometers are wire-wound, they are very stable and can be made to any desired accuracy. The servo system is a simple one, and its accuracy is limited only by the backlash in the gears.

Continued from page 4

Components on trial

A. D. Johnston, Reactor Engineer, checks parameter records. All photos courtesy of AEC.

tem variables. A level-galvanometer channel continually indicates and records changes in reactor power level, and level-safety channels are included to trip the reactor if unsafe conditions threaten.

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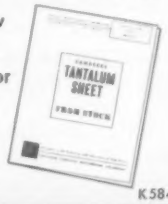
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Mathematical Basis

Some Xe^{135} is produced directly on fission, but the greater part of it is produced by decay of iodine-135.*

$$6.4\%\text{ of fissions} \longrightarrow Te^{135} \xrightarrow{\beta(2\text{ min})}$$

$$I^{135} \xrightarrow{\beta(6.7\text{ hr})} Xe^{135} \xrightarrow{\beta(9.2\text{ hr})} Cs^{135}$$

$$\leq 0.19\%\text{ of fissions} \longrightarrow Xe^{135}$$

The equations governing the concentration of I^{135} and Xe^{135} in a given region of the reactor are†

$$\frac{dI}{dt} = aP - \frac{I}{t_i} \qquad (1)$$

$$\frac{dX}{dt} = bP + \frac{I}{t_i} - \frac{X}{t_x} - cPX \qquad (2)$$

where I = concentration of iodine-135; X = Xe^{135} concentration; t = time; P = reactor operating power; t_x = mean life of Xe^{135} (13.28 hr); t_i = mean life of I^{135} (9.64 hr); and a, b, c, are constants for the particular reactor.

The computer solves Eqs. 1 and 2 continuously on a real-time basis, yielding instantaneous values of I and X. Thus, the effect of changes in reactor power on Xe^{135} concentration can be predicted. The prediction function can be most conveniently performed by a second analog computer solving the same equations but on a greatly accelerated time scale. Charts or tables can also be used but are restricted in versatility.

Equation 2 is a nonlinear equation because of the term $(-cPX)$, representing the destruction of Xe^{135} by neutron absorption. This requires a multiplier circuit in the computer. The rest of the terms in Eqs. 1 and 2 can be handled by two integrators and appropriate summing networks.

The solution of Eq. 1 for constant input power P and with $I = I_0$ at $t = 0$ is

$$I = t_i aP + (I_0 - t_i aP)\epsilon^{-t/t_i} \qquad (3)$$

* R. J. Cox, J. Walker, *Proc. I.E.E.* **103**, 577 (1956).

† F. S. Goulding, A. G. Ward. Reactor xenon poison simulator, AECL report CREL-597 (1955).

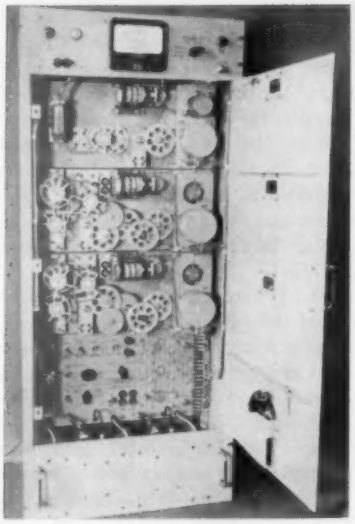

FIG. 1. Mechanism of computer

The solution of Eq. 2 for constant P and an initial I value of I_0 is

$$X = \frac{(a+b)P}{cP + 1/t_x} + \frac{(I_0 - t_i aP)\epsilon^{-t/t_i}}{t_i(-1/t_i + 1/t_x + cP)} + D\epsilon^{-t(cP+1/t_x)} \quad (4)$$

The constant D depends on the initial value of X. If we let $X = X_0$ at $t = 0$, substitution in Eq. 4 readily yields a value of D in terms of X_0 and the other constants.

I^{135} and Xe^{135} concentrations are plotted against time (Eqs. 3 and 4) in Fig. 3 for arbitrary values of a, b, c and for two constant values of P.

The first part of the graph shows the buildup of I^{135} and Xe^{135} concentration from shutdown ($P = P_m$, $I_0 = 0$, $X_0 = 0$). The value of the constant D in Eq. 4 during buildup (D_b) will be:

$$D_b = \frac{-(a+b)P_m}{1/t_x + cP_m} + \frac{aP_m}{1/t_x + cP_m - 1/t_i} \quad (5)$$

After the concentrations reach their equilibrium values (theoretically after infinite time), P is reduced to zero and the equations plotted with equilibrium values substituted for I_0 and X_0. The second part of Fig. 3 then plots Eqs. 3 and 4 with $P = 0$, $I_0 = t_i aP_m$, $X_0 = (a+b)P_m/(1/t_x + cP_m)$.

The value of D in Eq. 4 after shutdown (D_s) is

$$D_s = \frac{(a+b)P_m}{1/t_x + cP_m} + \frac{aP_m}{1/t_i - 1/t_x} \quad (6)$$

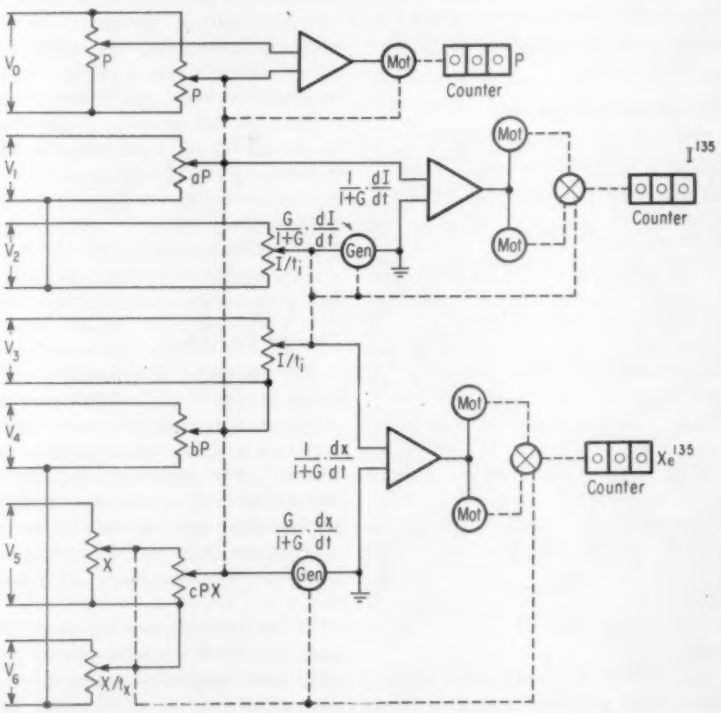

FIG. 2. Schematic of xenon-poisoning computer. Integrator circuits solve equations for I^{135} and Xe^{135} concentrations

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CROSS SECTIONS

This article starts on page 97

The I^{135} concentration builds up and decays exponentially. The Xe^{135} concentration comes to a maximum (X_m) after shutdown. It can readily be shown that X_m and the time t_m at which it occurs can be defined by

$$\log\left[\frac{t_x^2 aP_m}{D_s(t_x - t_i)}\right] = \left(1 - \frac{t_i}{t_x}\right)\log\left[\frac{t_x aP_m}{X_m}\right] \quad (7)$$

$$\log\left[\frac{t_x^2 aP_m}{D_s(t_x - t_i)}\right] = t_m\left(\frac{1}{t_i} - \frac{1}{t_x}\right) \quad (8)$$

Mathematically, the condition for this rise to occur is that b be less than act_xP_m. In practical high-flux reactors, the term representing the direct formation of Xe^{135} on fission (b) is small enough and the burnout term (c) is large enough to produce this Xe^{135} peak after shutdown from full power.

In constructing a computer of the type described, the value of X_m is of interest as representing the maximum required range of the xenon counter and potentiometers.

Figure 3 also illustrates the high rate of change of Xe^{135} concentration (dX/dt) that can occur if the reactor power is increased when iodine concentration is low and the xenon has fallen to the poisoning-out level after power shutdown.

Computer Design

The computer circuit (Fig. 2) consists of a power follow-up servo, an integrator circuit to solve the I^{135} equation and an integrator to solve the Xe^{135} equation.

The computer derives its input from an extra slide wire in a conventional self-balancing potentiometer type of recorder that forms part of the reactor instrumentation. The excitation for this extra slide wire is derived from a bridge rectifier, direct current being used here to minimize the effects of pickup in the external leads. A servo motor powered by a magnetic amplifier drives the power follow-up potentiometer as well as potentiometers in the I^{135} and Xe^{135} loops. These latter introduce the power-dependent terms of the equations into the I^{135} and Xe^{135} integrators.

Integration is accomplished with a tachometer generator having a linear output-vs-speed characteristic. If a precision potentiometer is geared to the generator, the displacement of the potentiometer wiper will be proportional to the integral, with respect to time, of the generator output. In practice, the speed and generator output can be made proportional to a given amplifier input by driving the generator through the amplifier and a motor and using the generator output voltage as negative feedback into the amplifier.

The I^{135} integrator has as its input signal the algebraic sum of three signals—a signal proportional to power derived from a potentiometer driven by the power follow-up servo, a feedback signal from a tachometer-generator and a second feedback signal from the integrator output potentiometer. The signal from the output potentiometer is proportional to the I^{135} concentration, which is also indicated by a drum counter geared to the potentiometer.

A second section on the I^{135} integrator output potentiometer supplies the main input signal to the Xe^{135} integrator. A signal representing the direct formation of Xe^{135} on fission is supplied by a potentiometer driven by the power follow-up servo. Three feedback signals are also applied to the input of the Xe^{135} integrator amplifier—the tachometer-generator signal, a signal proportional to Xe^{135} concentration derived from a section of the Xe^{135}-integrator output potentiometer and a signal representing the burnout of Xe^{135}, derived by multiplying a signal from the Xe^{135}-integrator output potentiometer by a signal proportional to reactor power in a potentiometer multiplying circuit. A drum counter geared to the Xe^{135}-integrator output potentiometer gives a visual indication of Xe^{135} concentration.

Appropriate trimming potentiometers allow for scale factor adjustment.

Design Details

The operating frequency throughout is 400 cps to take advantage of the high-quality tachometer generators and servo motors available at this frequency. The generators are temperature-stabilized drag-cup types designed for sustained accuracy and linearity.

The precision potentiometers are servo-mounted for easy null adjustment.

The iodine and xenon loop amplifiers each consist of a gain-stabilized zero-phase-shift transistor pre-amplifier with high input impedance, followed by a two-stage half-wave magnetic amplifier. The power-loop amplifier con-

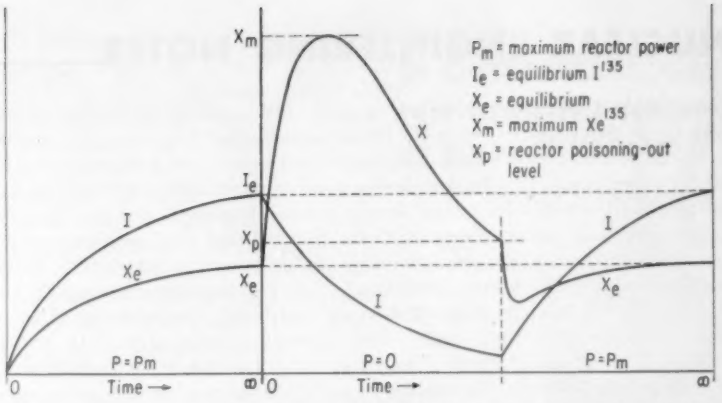

FIG. 3. Effect of reactor operation on I^{135} and Xe^{135} concentration. Poison buildup and decay are shown for full-power operation, shutdown and subsequent to shutdown

sists of a magnetic amplifier without the pre-amplifier.

The output of the magnetic amplifier in the I^{135} (or Xe^{135}) loop is connected to half of the split control field of each of two servo motors; the motor shafts are geared to differential drive. The other half of each motor control field is permanently energized, so that with no amplifier output, the motors run at half speed in opposite directions and the differential output speed is zero. The differential output is geared to a tachometer generator and precision potentiometers as explained above. Use of the two motors and differential enables an infinite ratio of generator speeds to be obtained without the adverse effects of motor slot lock and coulomb friction that occur with a single motor at very low speeds.

Shown on Fig. 2 are the terms of Eqs. 1 and 2 that are proportional to the various I^{135} and Xe^{135} counter readings and amplifier input voltages. The scale factors are determined by proper selection of gear ratios and adjustment of the voltages V_1–V_6. The loop gain G is defined as the ratio of generator output to amplifier input.

Thus the constants a, b, c, t_i, t_z are expressed in terms of voltage ratios, potentiometer and counter turns, gear ratios, tachometer-generator transfer functions and loop gains, to give the actual operating equations of the computer. Variations in supply voltage should have no effect on over-all accuracy inasmuch as this factor does not appear in the equations. Actually, line-voltage variations introduce slight unbalances in the magnetic amplifiers and matched motors driving the differentials.

The effect of gain variation alone can be seen from the following. Using Eq. 1, if the I^{135} loop is adjusted at a gain of G_1, which subsequently alters to G_2, the equation becomes

$$\frac{(1 + 1/G_2)}{(1 + 1/G_1)} \times \frac{dI}{dt} = aP - \frac{I}{t_i}$$

The equilibrium value (iodine concentration at infinite time) is unaffected. For gains much greater than unity, the maximum error (occurring at $t = t_i$), expressed as a fraction of maximum concentration ($t_i aP$), is

$$\text{error}/t_i aP = (1/G_2 - 1/G_1)\epsilon^{-1} = 0.37\ (1/G_2 - 1/G_1)$$

The effects on over-all accuracy of unbalance, drift, generator null voltage and loading on the potentiometers and generators can all be evaluated in fairly straightforward fashion. Generator residual (no-speed) voltage, for instance, is cancelled at the amplifier input (with output counters set at zero) by inserting an equal and opposite voltage from one of the precision potentiometers; this is accomplished by revolving the potentiometer slightly on its axis. The settings of these potentiometers at "zero" position must be taken into account in any over-all analysis of accuracy.

Maintenance and adjustment facilities are provided for setting up and checking circuit parameters. These include voltage and current metering, loop-gain measurement and provision for simulating a given set of reactor conditions by manually inserting into the computer any values of P, I or X within the range of the equipment.

* * *

The writers wish to thank Dr. A. Pearson of Atomic Energy of Canada, Ltd., for his interest in this project and valuable advice.

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NUCLEAR ENGINEERING NOTES

Gas-Cooled Reactors Still U. K. Favorite

After taking stock of two years of Calder-Hall experience, the British have decided that gas-cooled reactors look even better than before. In a recent lecture Sir John Cockcroft said that further development of power and propulsion reactors in Britain will concentrate mainly on high-temperature gas-cooled reactors moderated with heavy water or graphite. He observed that the "possible economic advantages of the sodium-graphite reactor did not seem to outweigh its serious development and maintenance problems." Likewise the Atomic Energy Authority will not "pursue the pressurized-water- and boiling-water-reactor types for large-scale power." However since these are the "mainstay of the U. S. and the U. S. S. R. programs at present," he noted, "they can not lightly be dismissed." The AEA feels these two reactors enjoy a capital-investment advantage but suffer a very serious fuel-cost disadvantage. Assuming maximum potential development, the British calculate that the difference in fuel costs alone (in Britain) would amount to 0.7 pence/kwh (6 mills/kwh).

In reviewing Britain's gas-cooled experience to date, Sir John said that Calder-Hall behavior over the last 22 months has been "remarkably good" and that the principal technological uncertainties have been resolved. Full-power load factors higher than in most conventional plants have been achieved. Power-level changes are now being made at rates of the order of 10 Mw(th)/min. With reference to the safety question posed by the Wigner-energy-release accident at Windscale (NU, Dec. '57, 43), the thinking is that a Wigner release may not be necessary during the lifetime of the power stations now being built since their lowest temperatures are 20° C higher than in Calder Hall.

Cockcroft also disclosed that in the Windscale incident three tons of uranium had been oxidized. In spite of this "major fire" he maintained that the public health hazard could have been avoided had the stack filters been ten times less permeable.

Fuel elements. Only three fuel elements of the 10,000 in Number One Reactor at Calder have failed. "Slight faults" in the sheaths of the three elements have allowed an inleakage of CO_2 slowly to oxidize the uranium metal and release fission products. Even so no emergency shutdowns were necessary; replacement of the defective elements was scheduled for regular maintenance shutdowns. The Magnox-cladding failures were believed to be the result of fuel growth and could be eliminated by increasing the ductility of the Magnox.

Fuel-element life is thought to be limited by the internal pressure of fission-product gases. These may build up in small bubbles to pressures of several hundred atmospheres. In the temperature range 450°–600° C (840°–1,100° F) the volume expansions caused by this internal pressure are of the order of 10% at 3,000 Mwd/ton (the exact amount depends on metallurgical imperfections). The Magnox cans are being redesigned to accommodate such expansions. An extensive testing program in the Calder reactors to develop fuel elements for civilian power reactors is envisioned.

Advanced reactors. Plans for advanced-design gas-cooled reactors exist in two versions—one moderated with graphite, the other with D_2O. The objective in the graphite model will be to decrease capital costs per kw 30% by increasing the fuel-element-surface temperature to about 600° C (1,100° F). By using clusters of smaller-diameter fuel elements, the average thermal rating would be increased to 8 Mw(th)/ton. To get to these temperatures the AEA will change from a uranium-metal to a sintered uranium-oxide meat. Beryllium would probably be used for the cladding. Fuel elements with beryllium cans have already been fabricated by the AEA and thermal-cycled hundreds of times through the alpha-beta transition point without damage. The first specimen is now going into DIDO for irradiation tests.

The advanced graphite reactor will use slightly enriched fuel. This together with the higher performance requirements will increase fuel-element costs. However, the greater irradiation stability and thermal efficiency should permit about twice the heat output per ton so that over-all fuel costs will be about the same as the first-generation reactors (about 0.16 pence/kwh). With capital costs of the order of £80/kw(e) and for the 70% load factor predicted in the late 1960's, the total power cost would come down to 0.47 pence/kwh.

According to British thinking, a D_2O-moderated gas-cooled reactor, since it is smaller than the graphite type, should also be able to reach a capital investment

of £80/kw(e). About £10–15 of this amount would be invested in D_2O. (D_2O production has been studied at Harwell during the last few years.) Furthermore the excellent neutron economy of the D_2O makes for low fuel costs. Thus the over-all economics of gas-cooled D_2O reactors appear as favorable as the graphite variety.

For the ultimate gas-cooled reactor the British see fuel elements clad with ceramic instead of metal. This might allow an increase in gas outlet temperature to 700° C (1,300° F). The AEA is attempting to develop impervious ceramic cladding for a ceramic fuel element containing graphite, uranium and thorium. A zero-energy experiment now being built at Winfrith Heath will study the nuclear properties of the reactor at high temperature. If successful this reactor might have applications to propulsion.

Fast-breeder outlook. Sir John indicated that the favorable record of the gas-cooled thermal reactors may be shifting British long-range plans away from the fast reactor concept. Although it had been announced that Britain expected to rely heavily on fast power reactors (of the Dounreay type) after 1980 (NU, Dec. '57, 24), Cockcroft observed that, since the supply of uranium available to the West is now more than necessary to support any foreseeable nuclear-power program up to the late 1970's, the original urgency for fast-reactor development has largely disappeared. The main problem is to find the most economical way of burning the by-product Pu from thermal-reactor stations. Whether or not this can best be done in thermal reactors or fast reactors is something the British hope to resolve when Dounreay goes critical.

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Last September Congress authorized the AEC to consider the pros and cons of starting two new reactor projects. The first had to do with whether new improved versions of the Hanford Pu-production reactors should generate electric power as a by-product. The second was to explore the feasibility of adding a gas-cooled, graphite-moderated reactor (an advanced Calder Hall type) to the U. S. power-reactor development program. Last month the AEC presented its findings to Congress on both of these ideas. NUCLEONICS has summarized the main points and conclusions in these two articles

AEC reports to Congress on . . .

1. Gas-Cooled Power Reactors

To study gas-cooled graphite-moderated reactors Kaiser Engineers was selected (from thirty-one interested companies) as a prime contractor, with ACF Industries, Inc., as subcontractor to provide assistance on nuclear calculations and reactor design. The scope of work on gas-cooled, graphite-moderated power plants assigned to Kaiser included:

- feasibility study of a full-scale, natural-uranium-fueled plant optimized for minimum cost of power.
- preliminary design of a 40,000 kw(e) prototype for such a plant, including evaluation of plant operation with partially enriched as well as natural uranium.
- feasibility study of a full-scale, partially enriched-uranium fueled plant optimized for minimum cost of power.
- feasibility study of a prototype for this last plant.

The study yielded these major conclusions about gas-cooled graphite power reactors: The United States has enough technical knowledge to start today (if it wanted to) building reactors of this type as advanced in design as any now being built. These plants would not yield competitive nuclear power in the United States but show promise of this granted future improvements. The economic potential of gas-cooled graphite-moderated reactors using slightly enriched uranium fuel is definitely superior to that of natural-uranium-fueled concepts. An exception to this might be Pu-recycling with natural-uranium feed, but too little is known yet about Pu-fuel technology to say for sure.

Technical Problems

The major problems associated with the design of a gas-cooled graphite-moderated reactor power plant are choice of coolant gas, fuel materials, and major equipment such as the pressure vessel and steam generator.

Although helium has problems of availability (especially for foreign countries) it is preferred over CO_2 as a coolant gas since CO_2 appears limited by graphite oxidation to temperatures below 1,000° F. As to fuel materials, natural-uranium elements using metallic meat and Magnox clad are felt to be limited to temperatures below 800° F by buildup of fission-product gas. With a slight enrichment a UO_2 meat and stainless clad could be used, allowing much higher temperatures. Although major components (especially for helium-cooled systems) have yet to be developed, no really serious difficulties are foreseen. Fabrication of large pressure vessels will not significantly limit plant capacity.

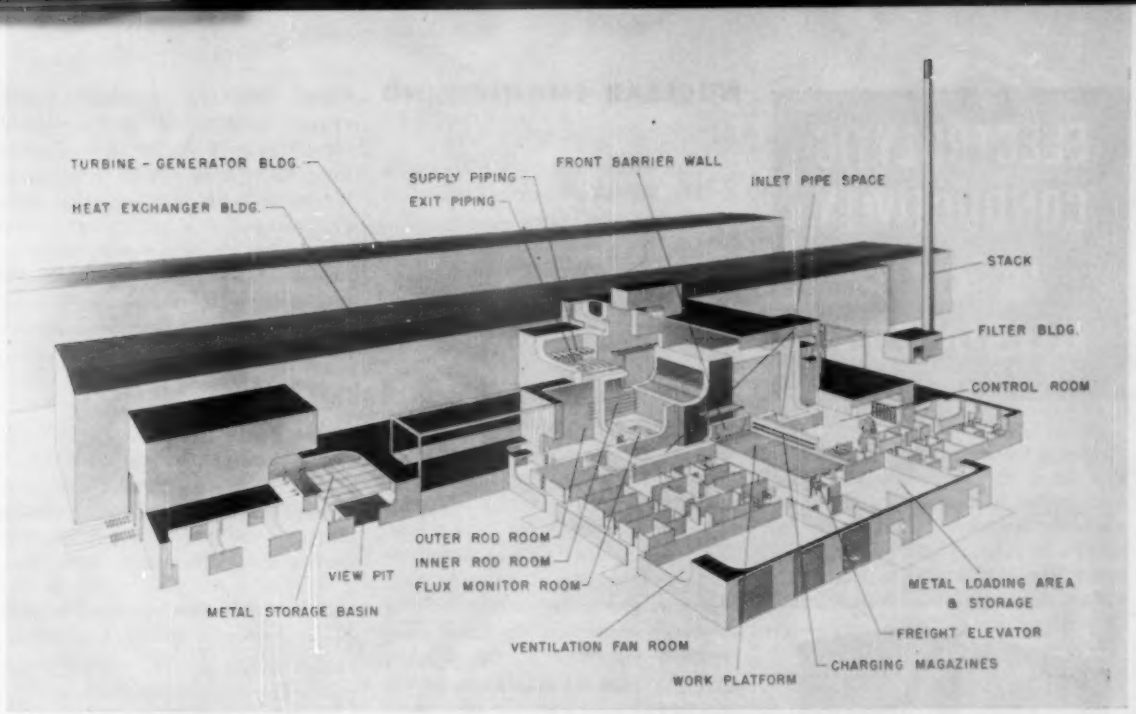
Enriched vs. Natural U

Gas cooled reactors which could be designed now for use with partially enriched fuel appear capable of superheating steam to temperatures of 1,000° F at pressures over 1,000 psig. These steam conditions approach those used in modern conventional steam plants and result in net thermal efficiencies of 30 to 35%. Plant capacities in excess of 200,000 kw(e) are feasible.

Plants of this type could be built in the United States during the next 5 to 6 years for $400–$500/kw(e) (exclusive of working capital, interest during construction and cost of first core). The 215-Mw(e) plant designed by Kaiser Engineers would have a total power cost of 13.4 mills/kwh assuming 9,000-Mwd/ton fuel exposure.

How would a natural-uranium reactor compare with this performance?

Continued on p. 146



DUAL-PURPOSE plutonium production reactor proposed by General Electric Co. as possible successor of existing Hanford piles

2. Dual-Purpose Production Reactors

Interest in Pu-production reactors stems from the realization that the present facilities at Hanford (which began operation in the fall of 1944) will have to be replaced before too long. It is also known that the power produced by the three existing reactors at Hanford is very large by utility-station standards. The question has been raised as to whether the government could reduce the cost of making Pu in the replacement facilities by converting some of this power (which is now dumped into the Columbia river) into saleable electricity. Thus the AEC asked for a study of the relative advantages of dual-purpose designs as well as an improved version of the existing single-purpose reactors. The conclusions reached by the General Electric team that did the study were (1) the design reactor as a single-purpose facility would produce Pu in larger quantity and for lower costs than any competing concepts. (2) A dual-purpose plant with the same Pu-production rate and a moderate by-product power output [300 Mw(e)] would have no significant cost advantage at Hanford. (3) A dual-purpose concept generating large [700 Mw(e)] amounts of power would have significantly lower Pu costs but the *rate* of production would also be significantly lower.

Arguments For Dual-Purpose Reactors

Production-only reactors are an economic waste.

It would prove cheaper for the government to buy additional Pu from industry than build more government-owned plants.

Government purchase of Pu would do away with the need for a direct subsidy for industry.

Even power-only reactors proposed by industry today count on selling Pu at weapon-grade prices. Why not recognize this?

Today's military production requirements may turn out to be a permanent way of life.

Arguments Against Dual-Purpose Reactors

The eventual aim is an economic power-only plant—so why not concentrate on this from the beginning.

Crediting Pu with its weapon value instead of its fuel value will shift reactor development in a direction that will prove to be unrealistic for the long-range power interests of the nation.

An extensive dual-purpose program would produce more Pu than we would need.

Growth of peaceful atomic energy would be inhibited by associating it with a defense effort (e.g., dual-purpose production-facility data would be classified).

The larger capital investment needed for dual-purpose plants would make industrial participation more difficult.

From a manuscript by A. B. Greninger, Hanford Atomic Products operation, General Electric Co., Richland, Washington.

Reactor Study Scope

The G. E. study covered these specific objectives:

- Estimate the capital and operating costs of single and dual-purpose facilities.
- Calculate Pu production rates and

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NUCLEAR ENGINEERING

Continued from p. 105

unit costs for single-purpose operation and for a range of by-product electric-power outputs.

- Outline the development work required for the alternate concepts.
- Develop preliminary schedules for construction and operation of the concepts considered.

Reactor Concept

The reactor (see figure) consists of a large block of graphite pierced horizontally by zirconium-alloy process tubes that contain the fuel elements and provide channels for coolant flow. The contemplated fuel elements are clusters of cylindrical uranium rods. The graphite stack is comprised of thousands of pieces of machined, reactor-grade graphite. Special passages are provided in the graphite to permit venting of steam from the tube channels in the event of a tube rupture.

For the plutonium-only case, the primary coolant would be demineralized water, recycled through the reactor and heat exchangers under pressure. The secondary coolant would be river water, pumped from the river through the heat-exchangers and then back to the river. For the dual-purpose cases, the secondary-circuit boiler feed water is pumped to the steam-generation heat-exchangers. The steam produced operates the primary pumps and supplies the turbogenerators. The condensate from these facilities is recycled back, supplemented by demineralized water make-up. Condenser cooling water is taken from, and returned to, the river.

For either the single or dual-purpose versions, the major development problems would be (a) fuel-element design, (b) operation of the graphite at high temperatures, (c) process-tube design and (d) design of the emergency vapor-venting system. All are considered capable of solution but in some cases the solution may not be available at the earliest projected startup date. For instance, if a high integrity fuel element has not been developed by the time the reactor begins operation, the suggestion is to use the best available element at some sacrifice in reactor performance.

Three Types

Six alternate versions of the basic reactor concept were studied in detail; these gave rise to six additional generalized reactor designs. Three cases that span the range of conditions covered by the studies are:

Plutonium-only reactor—capital cost: $126-million

Design would provide for plutonium production only, utilizing conventional heat exchangers, with no provision for conversion to dual-purpose operation. The pressures in the primary loop are only as high as need be to prevent boiling while carrying away the heat generated. Water in the primary loop is circulated by conventional electric-driven pumps.

Plutonium-power reactor [300 Mw(e)] —capital cost: $198-million

The reactor would operate at a high power level to produce plutonium at the same rate as the single purpose reactor above plus 300 Mw of electric power. At a reduced power level, plutonium production rate would be lower if the 300-Mw(e) output is maintained.

Plutonium-power reactor [700 Mw(e)] —capital cost: $256-million

This reactor would operate at a lower power level and Pu-production rate

Plutonium Cost Comparison

	Plutonium-only	*Plutonium plus 300 Mw(e)*	*Plutonium plus 700 Mw(e)*
Capital costs ($10^6$$)	126	198	256
Plutonium unit cost (% of cost for Pu-only reactor and ten-year Pu demand)			
Full cost basis			
Ten-year Pu demand*	100%	105%	71%
Twentyfive-year Pu demand	78%	73%	49%
Incremental cost basis			
Ten-year Pu demand*	88%	90%	49%
Twentyfive-year Pu demand	66%	61%	34%

* Pu credited at fuel value of $12/gm during power-only period.

than the single-purpose design but would have a 700 Mw(e) output. The heat-removal and steam-generation systems would be similar to those of the 300-Mw(e) reactor except for size and capacity.

Many variations on these three cases are possible, particularly with respect to: the amount of electric-power equipment installed at the time of construction, the provisions made during construction for subsequent installation of initial or additional power-generating equipment and the timing of any such installations.

With the reactors above, for a single-purpose reactor with provision built in for subsequent installation of moderate amounts of electric power, the initial capital cost would be $151-million (as compared with $126-million for no power provision); installing the generators, etc., would cost about $59-million bringing the total cost for the plant and auxiliaries to $210-million (as compared with $198-million for the 300-Mw(e) unit mentioned above). Similarly, a unit built for conversion to large amounts of electric power would cost $191-million (vs. $126-million), and later power-equipment installation would cost $75-million if done in one step, and $83-million if done in two steps, making the total costs $266-million or $274-million [vs. $256-million for 700-Mw(e) reactor above].

Economics

The over-all economics of both single- and dual-purpose reactors depend on assumptions about site location and method of financing. Although some estimates were made for a reactor at sites other than Hanford and for private financing, the emphasis was on a production reactor built and operated with government financing at the Hanford site. "Government" financing includes amortization, cost of U fuel consumed and labor, materials and services needed for operation but does *not* include interest on capital investment and fuel inventory, process development costs and allowances for insurance, taxes and profit. The table shows unit Pu costs calculated on this basis for the three reactors relative to the Pu cost for the single-purpose reactor. Figures are presented both on an "incremental-cost" basis (only the actual additional expenses to the AEC of adding another reactor are considered) and a "full-cost" basis (the new reactor bears its pro-rata of over-

Continued on p. 146

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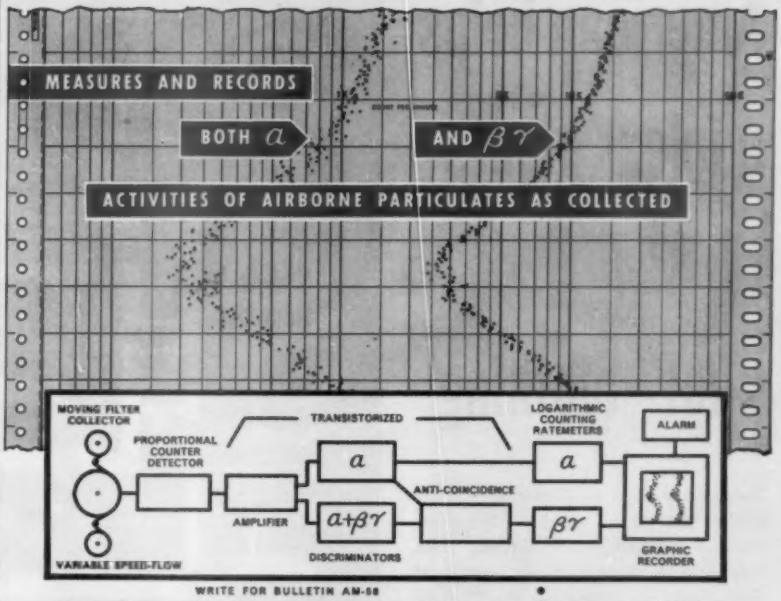

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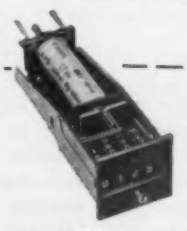

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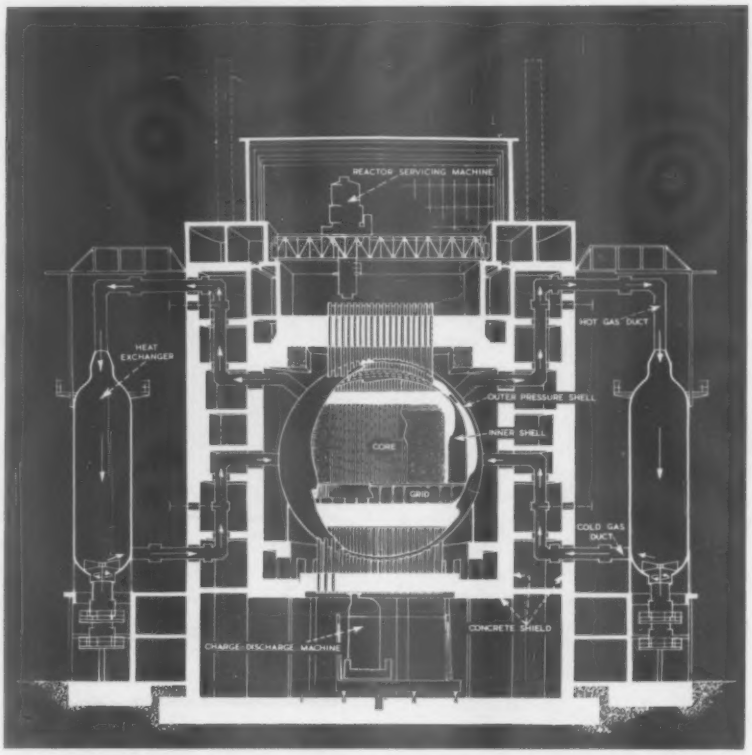

FIG. 1. One of two reactors being built at Hunterston, Scotland. Seventy-foot-diameter spherical containment shell is of double-wall construction. Note charge-discharge (refueling) machine below reactor; it can refuel while the reactor is in operation

Gas-Cooled Reactor for the South of Scotland Electricity Board

By P. J. GRANT

The General Electric Co., Ltd., Erith, Kent, England

At Hunterston, on the Firth of Clyde some 35 mi S. W. of Glasgow, Scotland, construction is under way on a two-reactor nuclear-power station for the South of Scotland Electricity Board (SSEB). In common with the other British nuclear-power stations, the basic physical properties of the two reactors are similar to those of the Calder Hall station (*1*). The main difference between the SSEB station and Calder Hall is to be found in the fact that the purposes of the stations are different. Calder Hall was designed for both plutonium production and electricity generation, whereas the SSEB design is for a base-load plant operating at a high load factor. Also, technological advances in the engineering of commercial nuclear-power stations, particularly marked in the SSEB project (*2*), have inevitably had their effect on some aspects of the physical design.

As in the Calder Hall reactors, the natural-uranium fuel will be contained within a pile of graphite and the heat generated will be transferred by circulating CO_2 under pressure. The cylindrical core (see Fig. 1) of each of the two reactors will be built up of graphite blocks that contain vertical fuel-element and control-rod channels. Each of the 3,288 fuel-element channels contains ten fuel elements stacked one on top of the other. The elements consist of rods of natural-uranium metal sealed in a magnesium-alloy can that has heat-transfer fins on its outer surface.

TABLE 1—Characteristics of the South of Scotland Reactor

Location:	Hunterston, Scotland
Type:	gas-cooled pile
Output—thermal:	530,000 kw
—electrical:	180,000 kw (gross)
Core	
Configuration:	cylinder
Size:	44.5 ft dia × 23 ft
Fuel—material:	natural U
—load:	250 tons
Control rods	
Number:	158
Absorber	
—material:	boron-steel
—length:	21.3 ft
Fuel elements	
Type:	rod
Number:	32,880
Rod dimensions:	1.15 in. dia × 24 in.
Canning:	Magnox A.12
Moderator	
Type:	graphite
Total inventory:	2,000 tons
Lattice pitch:	8.25 in.
Channel dia.	
—central:	4.1 in.
—outer:	3.8 in.
Coolant:	CO_2

Lattice Properties

The principal lattice and core dimensions appear in Table 1. The lattice properties were computed by standard methods and are based on exponential and fine-structure measurements carried out by the U. K. AEA.

At the present time, the capital cost of the station represents a higher proportion of the cost per net kilowatt-hour than does the fuel cost. The lattice parameters are therefore optimized with the aim of obtaining maximum heat output from the reactor rather than obtaining a very high conversion ratio. The lattice pitch and uranium rod size are chosen so that k_∞ is very near its maximum value for a graphite-and-natural-uranium system employing large coolant channels.

Table 2 is a summary of the lattice parameters in both the cold and hot (poisoned by-xenon) conditions. The figures are averaged over the entire reactor and refer to the initial state with a fresh fuel charge.

Slowing-Down and Diffusion Areas

In any reactor of this type, because of the large channels for the gas coolant, considerable axial and radial asymmetry exists (*3*). In the present design, the asymmetry is further enhanced because of the method of fuel-element support that is used. Each fuel element is supported individually within a cylindrical graphite sleeve (see Fig. 2). The fuel-element sleeves are stacked within a channel in the fixed graphite structure. There exists, therefore, neutron streaming, not only up the gas channel inside the sleeve, but also up the annulus that surrounds the sleeve. (The annulus is required to give sufficient mechanical clearance for refueling.) As a result, the ratio of migration areas is ~1.15.

Flux Distribution

The core dimensions represent a compromise between the physical requirement of minimum over-all neutron leakage and the demand, from the heat-transfer aspect, that the gas channels should be as short as possible to minimize the pumping power.

In computing the over-all flux distribution, a two-group method was used with allowance being made for the asymmetry of the slowing-down and diffusion areas. The axial and radial neutron leakages given in Table 2 were calculated by the one-group method for an unflattened reactor. When these are compared with the value of

TABLE 2—Lattice Parameters

Parameter	*Reactor condition*	
	Cold, clean	*Hot, with Xe*
Thermal utilization factor, f	0.918	0.906
Resonance escape factor, p	0.899	0.891
Fast-fission factor, ϵ	1.028	1.028
Thermal-fission factor, η	1.278	1.257
Multiplication constant, k_∞	1.084	1.043
Axial leakage	—	0.021
Radial leakage (unflattened)	—	0.012

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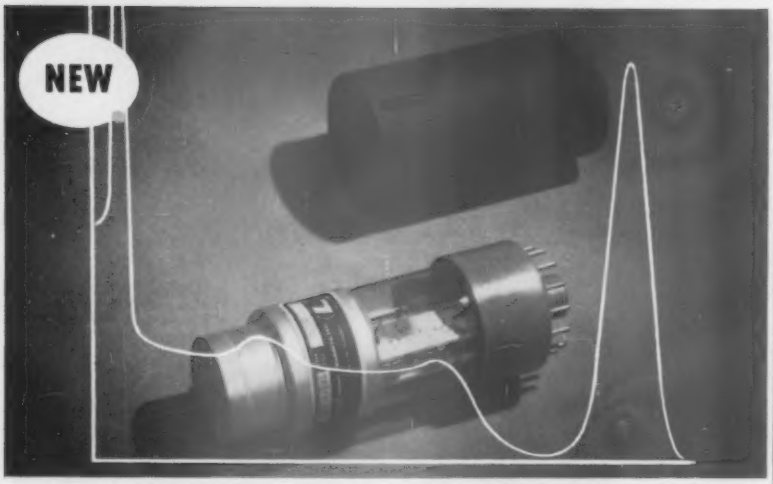

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k_∞ during operation conditions, it is apparent that there is excess reactivity available that could be used either to flatten the flux distribution or to increase fuel burnup. This excess reactivity has been used for flux flattening. The flattened radius is 11 ft (almost 50% of the core radius).

The flattening will be carried out initially by replacing fuel elements in some channels in this zone with steel bars. Later in the life of the reactor, these bars will be withdrawn and the flattening carried out by running this zone of the reactor with more highly irradiated fuel than the outer zone.

The average power density of the reactor is 2.11 Mw/tonne* of uranium, giving a total heat output of 530 Mw.

Control Rods

There are 208 control-rod channels in all, one in the center of each group of 16 fuel channels. Only 156 control rods are actually provided and these have a total worth of about 8.5% $\Delta k/k$. The rods are distributed in four groups: a fine group of four rods, each controlling $\sim$0.1% $\Delta k/k$; a safety group controlling 1.25% $\Delta k/k$; and two coarse groups.

Of the unused control-rod positions, 14, spaced across a diameter of the core, are used for flux plotting by the same activated-wire technique that is used at Calder Hall.

Radiation Shielding

In determining the shielding requirements of the SSEB station, the philosophy adopted was based on four assumptions.

- Wherever personnel normally work, the combined dose rate from all radiations must be reduced below 1/5 of the maximum permissible level (mpl) of 0.3 r/week.
- At all points where regular but short work is performed, the level must be reduced below 1 mpl.
- Wherever work is performed only rarely, or wherever it is impossible to reduce to 1 mpl, a dose rate will be tolerated such that, in one day, the dose received will not exceed 1/5 of the

* Diminutive of *tonneau*, the unit of measure in the metric system that is equivalent to 1,000 kg. The tonne is equivalent to 1.1023 short tons and to 0.9842 long tons. The short ton is equal to 2,000 lb, the metric ton to 2,204.6 lb and the long ton to 2,240 lb.

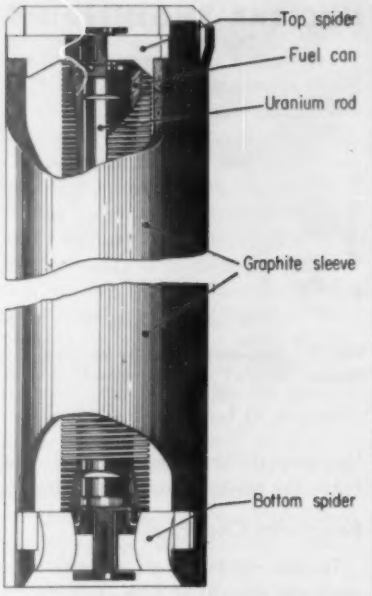

FIG. 2. Replaceable-channel fuel element is one of ten in each of 3,288 channels in graphite-block core structure

allowed weekly total and, further, that the dose received in any one week does not exceed the allowed weekly total.

• Wherever ingestion hazards might occur, either from graphite dust or active gas, the region will be monitored to determine the local dose rate.

To determine the shield thickness required, a two-group calculation through core, reflector, pressure vessel and concrete shield was performed to determine the neutron distribution that gives rise to gamma-ray emission from the different layers. It was found, as expected, that the shielding thickness required (9 ft for the walls and 10½ ft for the roof) is determined by the gamma radiation from neutron capture in the steel of the pressure vessel.

Shield Heating

In the Calder Hall reactors, a steel thermal shield is used to prevent radiation heating of the biological shield. This was not considered essential but was included as a precautionary measure. In the SSEB reactors, the double-shell construction of the containment shell, coupled with increased steel thickness in the pressure vessel, renders a thermal shield unnecessary. The only exception to this is over the top of the reactor where a boron-steel "umbrella" covers most of the core to remove the thermal neutrons streaming from the ends of the fuel channels. Below the reactor this is not necessary

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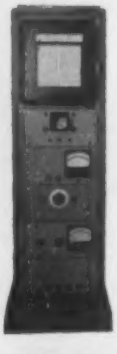

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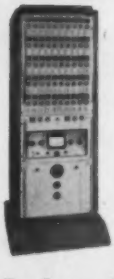

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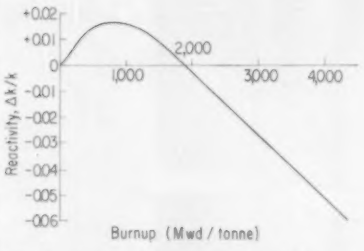

FIG. 3. Long-term reactivity variations as function of irradiation for point in reactor

because of the large masses of steel present in the reactor support structure.

Reactivity Changes

Despite the fact that the lattice dimensions were fixed with little regard for the conversion ratio, it turned out to be satisfactory, with the initial value being 0.825. Using this figure, and the cross sections appropriate to the reactor neutron spectrum and operating conditions, the long-term reactivity variation as a function of irradiation for a point in the reactor has been computed and is shown in Fig. 3.*

From this point-reactivity curve, a channel-reactivity curve can be constructed if allowance is made for the cosine variation of flux along the channel and if the appropriate statistical weighting is used. The reactivity changes for the reactor as a whole depend both on the radial flux distribution and on the fuel-cycling system adopted.

If a bulk-discharge fuel-cycling scheme were adopted, the fuel burnup would be 1,900 Mwd/tonne in the unflattened zone and 2,700 Mwd/tonne in the flattened zone of the reactor. (The increase in irradiation in the flattened zone corresponds to the removal of the steel flattening bars during irradiation.) The mean irradiation received would be ~ 2,100 Mwd/tonne.

In practice, this burnup can be greatly increased by either or both of two other fuel-cycling schemes that are made possible by the engineering design of the refueling machine. This machine operates from a chamber

* More recent data show that the original calculations (and the figures quoted in Table 2) were overly pessimistic and that excess reactivity will be available at startup. Engineering design considerations lead to the use of this reactivity to increase burnup rather than to seek a further increase in flattening the heat flux.

under the reactor (see Fig. 1) and can replace fuel elements while the reactor is under pressure and at full power.

The first fuel-cycling scheme would be to use the so-called "continuous" method of charge and discharge. With this method, instead of the bulk discharge of fuel carried out at Calder Hall, a few channels would be changed every day so that burnup would be continuously distributed. With this method, the positive reactivity change of the lightly irradiated channels could be used to balance the negative contributions of the more highly irradiated channels, and a considerable increase in irradiation time would be obtained.

The other scheme would be to carry out "axial inversion" of the fuel elements within a channel. In this process the refueling machine would remove the elements from a channel and replace them with the bottom set at the top of the channel and vice versa (the original order of fuel elements 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 becomes 6, 7, 8, 9, 10, 1, 2, 3, 4, 5). The least irradiated elements would then be at the center of the channel with the highly depleted elements at the ends. The result would be a further gain in irradiation of 400–800 Mwd/tonne, depending on the time at which the scheme was carried out.

To even out the burnup, and to avoid requiring an irradiation that, from the metallurgical viewpoint, would be excessive, radial movement of the fuel could be carried out by the refueling machine so that fuel elements in the 4.1-in.-diameter channels start their life in the unflattened region of the reactor and finish in the flattened zone. By carrying out the radial movement at the same time as the axial inversion, the number of operations by the machine would not be increased.

Over the reactor's lifetime, the mean irradiation of the fuel would not be as high as that of the fuel discharged during the continuous cycling scheme because of the time taken at the beginning to reach this cycling state and because there is unspent fuel at the end. Nevertheless, over a 20-yr life, the average irradiation would be >3,500 Mwd/tonne, with higher burnups for longer lifetimes. With present uranium prices, this corresponds to a net fuel cost of <2 mills/kwh.

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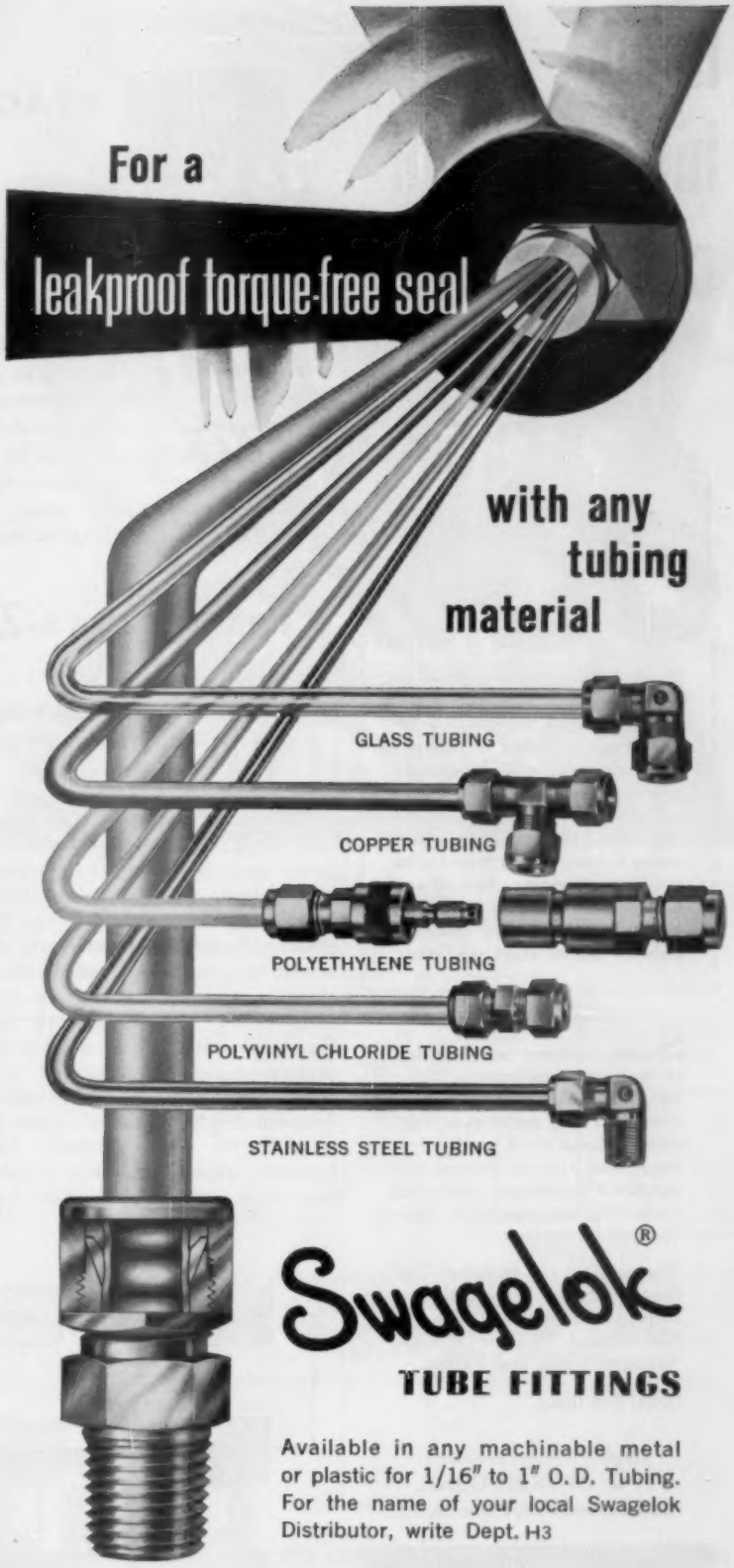
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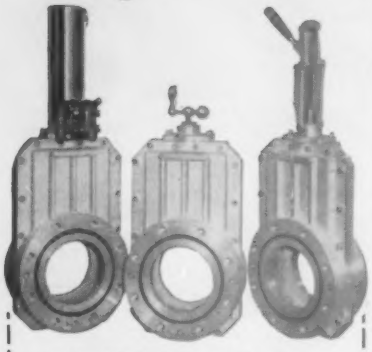

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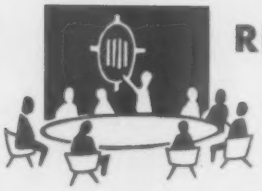

REACTOR ROUNDTABLE

A discussion place for new reactor ideas

Reactor Roundtable, a new feature in our Nuclear Engineering department, is devoted to ideas for new kinds of reactors. Such ideas are almost as numerous as reactor designers and invariably ingeneous, but often the inventor has not been in a position to make a really thorough evaluation of the reactor concept. Now this department can provide a forum by drawing on the wealth of engineering knowledge available among our readers to provide comments and criticism of these new ideas. We invite you to send your comments in the form of letters to the Reactor Roundtable Editor.

Temperature-Zoned Reactor

By F. H. CLARK and C. N. KLAHR
Technical Research Group, New York, New York

The temperature-zoned reactor system attempts to improve nuclear-power economics by supplying reactor heat at two different temperatures. In this way the requirements of the steam cycle for high temperature can be met without the waste of producing all of the reactor heat at the same high temperature. The reactor core (see Fig. 1) consists of two zones that are neutron-coupled but isolated in temperature from each other. The higher-temperature zone produces a relatively small fraction of the total heat. This high-temperature heat is used to superheat steam produced by the lower-temperature heat from the other zone. Note that separate coolant streams are used for each zone; the high-temperature coolant stream delivers its heat to the superheater and the low-temperature coolant stream delivers its heat to the boiler.

The economic advantages of such a design are based on two important observations: First, the amount of high-temperature heat required when water is the working fluid in the electrical generating system is relatively small. Since water has such a high heat of vaporization, in a reasonably efficient superheated-steam system a major part

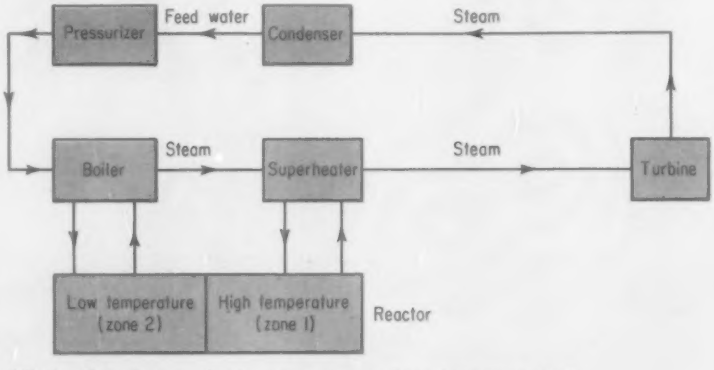

FIG. 1. Flow diagram for temperature-zoned reactor power plant

of the heat output goes into boiling the water so that the amount of heat used at high temperatures for superheating is a small fraction of the total. Second, high-temperature heat is more expensive to produce from a reactor than low-temperature heat. High-temperature reactor-core materials generally are more wasteful of neutrons and more expensive to fabricate: system plumbing and components must operate at higher pressures and therefore are more costly.

Thus, instead of designing the whole core to operate at superheat temperatures, it may make sense economically to separate the core into two regions, one producing heat at high temperatures and the other at low temperatures.

A key feature of the temperature-zoned design is the use of separate coolant streams* (see Fig. 1) as opposed to a double-pass single-coolant stream. It can be readily shown that separate primary-coolant streams require less high-temperature heat to achieve the same steam cycle conditions than a single primary-coolant stream in a system containing two heat sources at different temperatures.

In the two-zone separately cooled system, reactor and coolant-flow control must be good enough to maintain the desired balance of power generation and heat removal between the two zones.

Designs Studied

Two temperature-zoned reactor applications have been studied: (1) A Calder Hall type modified to produce high-temperature heat with conventional materials while retaining natural uranium as fuel. (2) Pressurized-water types operating at either lower pressure or higher power density than conventional designs.

Calder Hall type. The Calder Hall type temperature-zoned reactor consists of four cylindrical regions plus a graphite reflector on top and bottom. The innermost region is a low-temperature gas-cooled region, containing a graphite matrix with natural-uranium fuel elements and magnesium-alloy cladding, similar to the fuel elements used in the Calder Hall plant. The magnesium cladding limits the coolant temperature to a 700° F maximum. This region has a $k_\infty > 1$ after full allowance for equilibrium xenon and temperature effects. (*continued, p 116*)

* The same kind of coolant is used, however, in each coolant stream.

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Gd	1350	3000	1.8	7.87	46,000
Dy	1400	2600	1.77	8.56	1,100
Er	1500-1550	2900	1.75	9.06	166

*Estimated

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At Bettis Atomic Power Division scientists in related fields often meet for discussion on various topics pertinent to the advancement of nuclear power technology. It is men like these who will one day give the world complete power over the atom.

One of these discussions led by Dr. R. S. Varga centered around a lemma proved by Stieltjes in 1887 which states that: "If the elements off the principal diagonal of the (symmetric) matrix of a positive definite quadratic form are all negative, then all the elements of the inverse of that matrix are positive."

Realizing the relevance of Stieltjes' lemma to nuclear power technology, Dr. Varga obtained several necessary and sufficient conditions that the inverse of a matrix has positive elements. He then established that the elliptic partial differential equation $-\nabla \cdot \left[D(\vec{x})\nabla\varphi(\vec{x})\right] + \Sigma(\vec{x})\varphi(\vec{x}) = S(\vec{x})$, arising naturally in multigroup diffusion problems, is numerically approximated by the matrix equation $A\vec{x} = \vec{k}$, where the matrix A satisfies one of the sufficient conditions above. Hence, if $\vec{k}$, a vector related to the source $S(\vec{x})$, is non-negative, then the solution of the above matrix equation is a positive vector.

the solution was a positive vector

A typical discussion period attended by (left to right) Mr. G. G. Bilodeau, Dr. R. S. Varga, Dr. J. Spanier.

Dr. Varga's calculations proved sound and the above fact has since been incorporated into a Bettis production code as an internal check. Dr. Varga and the other men who took part in this particular discussion typify the scientists who make up Bettis. Could you have added something to this discussion . . . or to one like it dealing with Physics, Metallurgy, or Nuclear Engineering? If your answer is yes; if you are a U.S. Citizen with a Ph.D. or the equivalent experience and would like to participate in the development of nuclear power, send your resume to: Mr. M. J. Downey, Dept. #A-47, Bettis Atomic Power Division, Westinghouse Electric Corp., Box 1468, Pittsburgh 30, Pa.

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REACTOR ROUNDTABLE

This article starts on page 114

The second region is a thin annular region of pure graphite surrounding the first region.

Next is a high-temperature gas-cooled annular region, consisting of a graphite matrix with uranium-oxide ceramic fuel elements, clad with stainless steel. This region will have a k_∞ substantially less than unity under operating conditions. The chain reaction in this region would not be self-perpetuating and is maintained by leakage of excess neutrons from the low temperature region. The outermost region is a pure-graphite-reflector annulus.

Flux and power calculations* for a simplified version of this reactor (with region 2 omitted) showed that 15% of the total heat would be produced in the high-temperature zone. (A more refined design could substantially increase this figure.) This would permit a steam cycle with steam-superheat temperature to about 850° F and a gross thermal efficiency of 39% on the basis of a simple Rankine cycle. A comparable efficiency in a conventional Calder Hall type reactor with maximum steam superheat temperature of 650° F is about 31%.

About 20% of the gross efficiency will disappear in turbine and generator losses, and about 10% will be required for gas-coolant pumping power.

Modern conventional power-plant cycles are more efficient than the Calder Hall thermodynamic cycle is. However, these cycles, which include regenerative heating of feedwater, multiple pressures and reheat, are not compatible with a 15% superheat ratio. For example, a 400° F feedwater temperature cannot be obtained by regenerative reheating unless the superheat ratio is about 40%. Such a ratio is possible with enriched fuel but not with natural-uranium fuel. We estimate that an optimized design for an unenriched temperature-zoned Calder Hall type reactor would supply up to 25% of the heat at high temperatures. This would permit fairly efficient regenerative reheating cycles.

PWR type. The conventional PWR-type design with a coolant exit temperature of 540° F (working-fluid maximum temperature about 500° F) requires an external pressure vessel

* In this calculation k_∞ for the low-temperature zone was taken to be 1.023, for the high-temperature zone 0.95.

rated at 2,000 psi. This is one of the important cost elements of the reactor. In a two-zone design this disadvantage could be eliminated as follows: One has a small inner zone taking about ⅓ the total volume and surrounded by an internal pressure shell rated at 1,400 psi and made of a structural material with low neutron absorption, a zirconium alloy for example; then an outer zone comprising ⅔ the volume surrounded by a 600-psi pressure shell. Radiation damage of the internal pressure shell would probably be the most important development problem in this design. The 350° F (saturation temperature corresponding to 600 psi) pressurized water from the outer zone would be used to boil the working fluid. The 540° F pressurized water from the inner zone would be used to superheat the steam.

This design would have a somewhat lower thermal efficiency than the conventional PWR type because of the lower coolant inlet temperature. However, it would replace the large 2,000-psi external pressure vessel with two less expensive pressure vessels. The design would also have a considerable advantage in safety. A rupture of the external pressure shell is much less likely for a 600-psi vessel than for a 2,000-psi pressure shell, and a rupture of the inner pressure vessel would have the blast contained within the reactor to a large extent. The economic advantage for this design would be the savings on the pressure shell minus the cost of a superheater, plus the savings in safety features (i.e., underground installation and extra blast protection), minus loss in thermal efficiency.

An alternative PWR type would use the two temperature zones to increase the total power output for a given reactor size. The fuel elements in the low-temperature zone of the reactor would operate with a film drop of 120° F in the coolant instead of a 60° F film drop (as in conventional designs), thus doubling the heat-transfer rate. However to do this both coolant inlet and outlet temperatures must be reduced so that, if no high temperature region were used, the added power would result in a much lower thermal efficiency. A central high temperature region with its own coolant stream and a separate superheater could raise the working fluid temperature to 500° F as in the conventional PWR. There would still be a slight decrease in thermal efficiency due to the lower coolant inlet temperature, but in compensation the proposed two-zone system would roughly double the power density in the reactor.*

This PWR design would retain the 2,000-psi external pressure shell and would include an internal divider of insulating material (carbon with stainless-steel cladding, for example) between inner and outer regions.

Note that this design retains the same pressure in both regions, but operates the coolant of each region at a different temperature.

* Besides heat transfer rate, there are two other possible limitations on power output: (1) the internal temperature of the fuel element and (2) the maximum economical pumping speed. In some conventional PWR designs neither of these limitations is important. The fuel-element temperature is much below its upper limit and would still be below this limit if the power density were doubled. The pumping speed is often given as 15 ft/sec and could be increased to 30 ft/sec without excessive pumping costs.

Rickover on Reactors, Real and Otherwise

A new concept generally describes a plant with the following characteristics:

1. It is simple.
2. It is small.
3. It is cheap.
4. It is light.
5. It can be built very quickly.
6. Very little development is required. It will use mostly "off-the-shelf" components.
7. The reactor plant is in the study phase; it is not being built now.

On the other hand, a real reactor plant can be distinguished by the following characteristics:

1. It is being built now.
2. It is behind schedule.
3. It is requiring an immense amount of development on apparently trivial items.
4. It takes a long time to build because of the engineering development problems.
5. It is large.
6. It is complicated.
7. It is heavy.

(From a paper by H. G. Rickover, et. al., Annual Meeting, Society of Naval Architects and Marine Engineers.)

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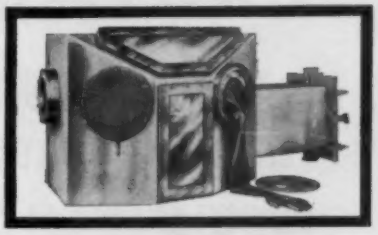

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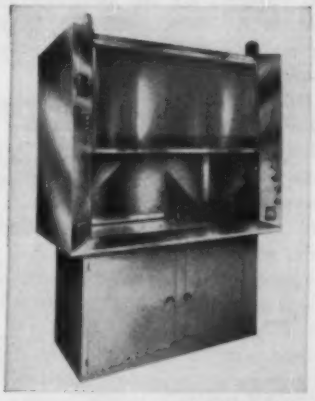

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Polyvinyl Chloride—New High-Level Dosimeter

By CHARLES ARTANDI and A. A. STONEHILL
Ethicon, Inc., Somerville, New Jersey

Polyvinyl-chloride film has been found to be a good dosimeter for electron doses in the 0.5–6-megarad range. It turns amber in color and a measurement of optical density indicates the absorbed dose within ~8%. Figure 1 is a photograph of several exposed slides. The film makes a cheap, simple, accurate and permanent dosimeter. After proper standardization it is equally good for gamma-ray dose.

We have used rigid nonplasticized film. Ordinary plasticized polyvinyl-chloride film is not suitable, because the plasticizer absorbs enough energy to prevent color formation.

A delay period for color development must be allowed after exposure. At room temperature optical density increases rapidly for three days and afterward at a much slower, uniform rate. However, when the irradiated slides are stored at 120° F, color development proceeds more rapidly and full intensity is attained at the end of 4 hr (Fig. 2).

Standard curve. Slides irradiated in 1-megarad increments are used to prepare a standard dose curve (Fig. 3). It is then a simple matter to check the dose of any subsequent irradiation by determining the optical density of an exposed slide and reading the corresponding dose on the curve. The following equation expresses dose in the straight portion

$$\text{dose}(megareps) = \log\left(\frac{\text{optical density}}{0.034}\right)^{-0.31}$$

It is important to keep the same supply of film throughout the experiments and to develop the color under standardized conditions (120° F, 4 hr). Otherwise the standard curve will change due to differences in composition or treatment. Composition differences within the same supply are negligible.

FIG. 1. Polyvinyl-chloride films exposed to high-energy electrons show increasing darkening with absorbed dose up to 6 megarad. Result is permanent after 4-hr storage at 120° F

Accuracy. If slides irradiated with known doses are used as color standards, 0.5-megarad differences can easily be detected by visual comparison of known to unknown. Spectrophotometer readings will show up differences as small as 0.1 megarad. Repeated exposures to the same dose in a single exposure or multiple exposures agree within ±8%.

Mechanism

In our opinion the mechanism of discoloration of irradiated high polymers is somewhat different from that of irradiated glass. The discoloration of glass is reversible while that of high polymers is not. Heat and prolonged storage or the combination of these will actually increase the optical density of irradiated polymers instead of reducing it as in glass.

Various types of glass discolor with irradiation. The color change can be explained by color-center formation. Electrons ejected by ionizing radiation are trapped at lattice vacancies (*F* centers) causing an absorption in the visible band (*1*). With storage at room temperature in ordinary light this color fades gradually. Exposure to heat or ultraviolet light accelerates the fading.

Discoloration. Some high polymers discolor with irradiation, but some do not. Polyethylene, polystyrene, polymethylmethacrylate irradiated to sev-

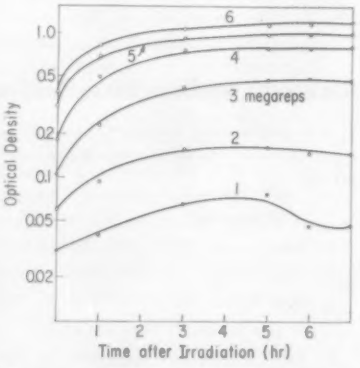

FIG. 2. After exposure optical density increases to saturation value. Optical density is log of reciprocal of fractional transmittance. Parameter labeling curves is exposure in megareps, rep being defined as 93 erg/gm absorbed in slides

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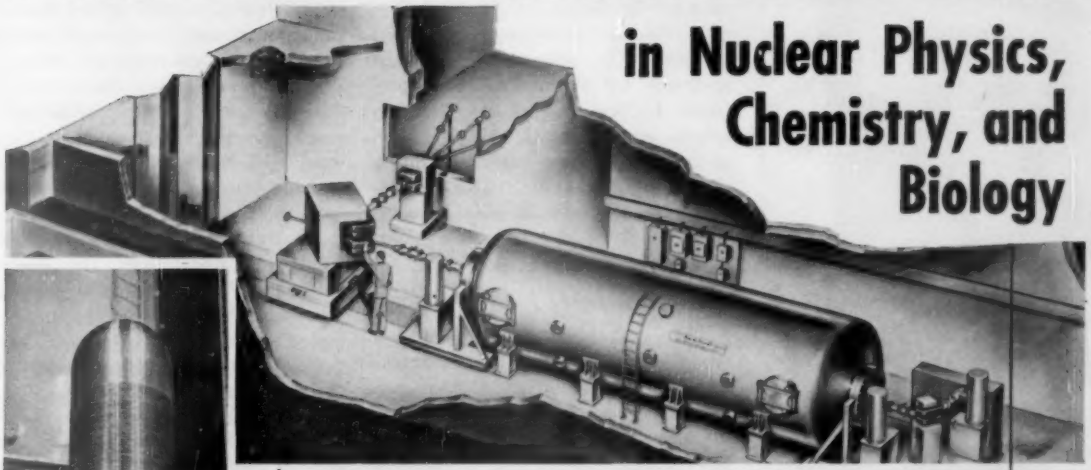

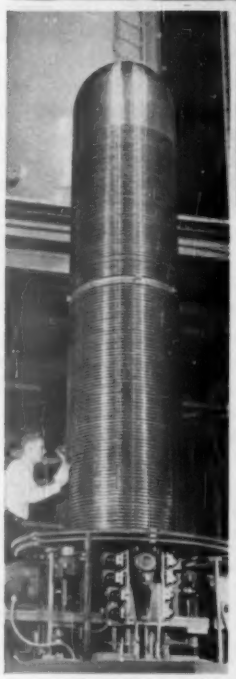

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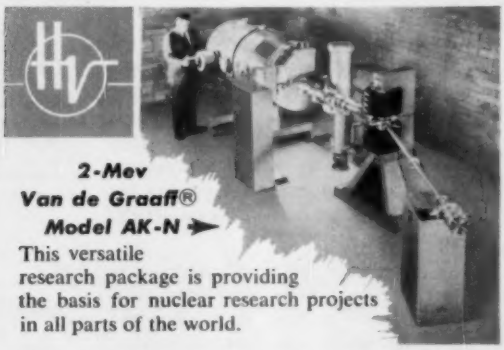

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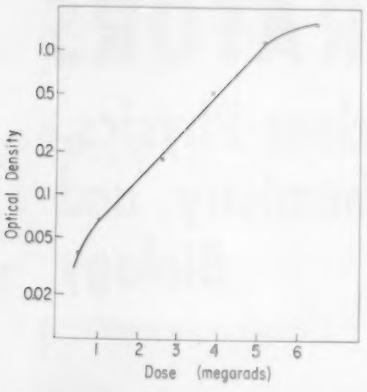

FIG. 3. Optical density is linear function of dose in 1.1–5-megarad range. Usable range is 0.5 to 6.5 Mrad

eral megareps show little or no discoloration, while polyvinyl chloride and polyvinylidene chloride discolor greatly (*2*). The hue generally changes from colorless through yellow to amber depending on the amount of ionization produced by the radiation source.

The discoloration of irradiated high polymers has been attributed to a mechanism similar to that of glass (*2*). Most electrons ejected from lattice-forming ions recombine to form the normal ions of the lattice, but some electrons are trapped at imperfections. The result is *F*-center formation and color development.

Other effects. Several other effects occur simultaneously with the discoloration and may take part in the process. It is known that gas liberation, double-bond and free-radical formation, oxidation, crosslinking, polymerization and degradation take place (*3*). Physical and crystallographical changes also occur.

When halogen-containing high polymers are irradiated, halogen or hydrogen halide is formed as a breakdown product. The amount of halogen or hydrogen halide liberated is proportional to the amount of ionization within certain limits. In polyvinyl chloride, irradiation causes evolution of hydrogen chloride. This process leaves double bonds behind. Some of these double bonds are probably conjugated.

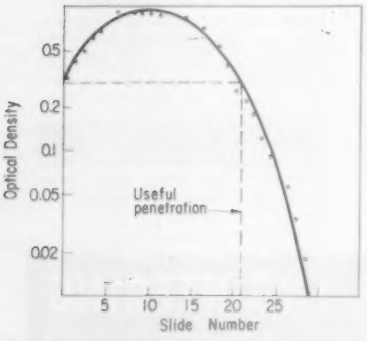

FIG. 4. Depth-dose curve shows optical densities of succeeding 3 × 1 × 0.10-in. polyvinyl-chloride slides in stack. Irradiation was to surface dose of 3.2 megarad with 2.1-Mev Van de Graaff electrons. Optical density was read at λ = 4,000 angstroms. Slides have a density of 1.38 gm/cm³

Other Dosimetry

There are other known dosimeters in the megarep range. Some investigators use the evolution of hydrogen chloride for measuring the amount of ionization (*4*, *5*). Henley and Miller incorporate a *p*H-sensitive dye into polyvinyl-chloride film (*6*). The hydrogen chloride produced by irradiation changes the color of the dye.

Silver-activated phosphate glass is a good personnel dosimeter, but in the megarad region its value is reduced by the nonlinear and decreasing dose response, and fading problems (*7–9*). Blue cellophane is an accurate dosimeter in the megarad range (*10*). One drawback is that the color change is not visible; optical density instruments have to be used. Moreover variations in thickness and dye dispersion require optical-density readings in the same spot before and after irradiation. Double readings make the process involved, but it is excellent for standardization work.

Photographic print-out paper has been proposed as a dosimeter (*11*). For accurate reading, it requires the use of instruments because visual accuracy is only about ±30%. Another drawback is that the dose rate cannot be more than 10^5 r/min, which is too slow for electron accelerators.

Experiments

In our early work with pharmaceutical sterilization by high-energy electrons in May, 1954, we noticed that rigid nonplasticized polyvinyl-chloride film developed a greenish coloration after irradiation. The color gradually changed to amber. We began to study the factors influencing the color change using a Van de Graaff 2-Mev accelerator.

Calibrating doses were calculated from meter readings of voltage and current in accordance with the manufacturer's instructions. Uniformity of the scan width and reproducibility of dose was also tested with blue cellophane dosimeters. Figure 4 is a depth-dose curve made by irradiating a stack of films and then reading each one.

Response and color development. Dose response and maximum color development were determined with 1 × 2-in. slides cut from 10-mil rigid polyvinyl-chloride film. Individual slides were irradiated to doses at 1-megarad increments in the range of 1–6 megarad. Immediately after irradiation, the slides were inserted in a Beckman spectrophotometer and the optical density read at λ = 4,000 angstroms. Readings were repeated daily for a period of two weeks. Later a faster color development was observed at elevated temperatures.

Films. Rigid polyvinyl chloride is a copolymer of about 90% vinyl chloride and 10% vinyl acetate. In addition the film contains a small amount of stabilizer. The film used in our experiment was of press-polished type in 0.010-in. thickness. It originated from Bakelite Company (VSA 3310 Clear 21, Gloss 0–3 0.010 in.) but is commercially available from plastic supply houses. The 3 × 1 × 0.010-in. slides cost about 0.4 cents each.

* * *

The authors acknowledge the valuable help of R. Hone and I. Medell in carrying out the irradiations and of W. Van Winkle, Jr. in his encouragement and valuable criticism. They are also grateful to the Bakelite Company for providing polyvinyl-chloride film and to the Du Pont Company for blue cellophane film.

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APPLIED RADIATION

Battelle to Catalog Radiation Effects Cataloging, evaluating, and disseminating information is the task of a newly founded Radiation Effects Information Center at Battelle Memorial Institute, Columbus, Ohio. The center has been established under a contract with the Air Force primarily for the purposes of the Air Force and its contractors. However, it is the plan to extend its services to other government agencies and their contractors.

Radiation effects is a big subject including such studies as damage to materials, chemical catalysis, food preservation, dosimetry, etc. Size and variety of the field and the barriers of company and military security restrictions lead to overlap and duplication of effort. One of the purposes of the REIC is to counterbalance this tendency, and it is likely that all radiation-effects programs will benefit.

Purposes. Primary concern of the REIC is gamma and neutron effects in materials in nuclear-powered aircraft outside the reactor and the crew compartment. Five specific objectives have been defined in an effort to make the Air Force radiation program as productive as possible. Data will be collected from open literature, the Air Force and its contractors, research and development reports from other government agencies, and personal interviews with researchers. Abstracts will be prepared by using direct quotations from the references and filed with multiple-listing techniques so that a researcher will find any reference under key words. These key words are selected by underlining in the prepared abstract.

This only starts the job; the REIC is intended to be much more than a library. Information will be critically evaluated and then disseminated in formal reports, technical memoranda, answers to inquiries, seminars and individual conferences.

Nine specific areas are presently covered by the REIC. They include (1) electronic systems, components, and materials; (2) electrical systems, components and materials; (3) hydraulic, pneumatic, and mechanical systems, components, and materials; (4) polymeric materials; (5) petroleum products and organic chemicals; (6) ceramic materials; (7) metals and alloys; (8) propellants; (9) nuclear radiation facilities.

Personnel. REIC's organization is such that Battelle's radiation experts, most of whose time goes to their own experiments, will contribute their talents on a part-time basis to interpreting data. Battelle's several departments will contribute them for advice and consultation as they are needed. The radiation experts will not be burdened with detail. This is handled by information analysts who process data, maintain files and assist visitors. A third group coordinates, supervises, and provides liaison.

Cloud Chamber Finds Dewpoints of Gases Compress a sample of air; wait for it to come to temperature equilibrium with its container; allow it to expand suddenly; look for tracks formed by ionizing particles supplied by a built-in radium source. This is the principle of the Alnor Dewpointer manufactured by Illinois Testing Laboratories of Chicago. If you don't see tracks the first time, you compress the next sample a little more and go on until you do. From the amount of compression required to produce tracks on expansion you can compute the dewpoint. This new use for the old cloud chamber brings it right back where it started; C. T. R. Wilson originally developed it in 1895 for the purpose of studying cloud formation.

Co^{60} Label Proves Auto Wax Quality Do you want to develop a better auto wax—or prove that you already have done so? One manufacturer felt his problem was to prove the pudding. With the consultation of a nuclear company he labeled his polish and four competing products with cobalt-60 naphthenate that would stay with the solids and indicate the thickness of the coating on application and after various kinds of wear—1 mc at a specific activity of 10 mc/gm was dissolved in mineral spirits and added to the melted waxes. Three areas of a car were divided into five sections each, and each section was polished with one of the test waxes. The car was driven across the country, and, sure enough, counting showed that the tester's wax led all the rest.

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AEC Reveals Principles of Stellarator, Pyrotron and DCX

On Friday, May 2nd the AEC lifted the curtain on thermonuclear researches underway in three of the laboratories that form part of Project Sherwood. The occasion was a special session on "Thermonuclear Enterprises" at the 1958 Spring Meeting of the American Physical Society.

What was provided was a fascinating, if brief, glimpse at the principles of the thermonuclear devices being explored at Princeton's Project Matterhorn, Oak Ridge and the University of California's Livermore Laboratory in talks by Lyman Spitzer, Albert Simon and R. F. Post, respectively. The three approaches differ substantially from the pinch effect and from each other. They reveal that there is more than one road to fusion power, though the basic elements of magnetic confinement and high temperature operation are still mandatory.

The revelations were not as detailed as those provided in the recent publication of material on U. S. and U. K. pinch-effect devices (NU, Feb. '58, p. 90). On the other hand they did provide an insight that many had not expected before the Geneva Conference, for which meetings complete details of the experimental fusion devices are still being withheld.

Because of the very considerable significance of these developments, NUCLEONICS has rushed this preliminary account of the operating principles into print. If further details are forthcoming they will be provided in an early issue. When the more complete revelations that are promised for the Geneva Conference take place, we will report those too.

Princeton's Stellarator

Like all other devices proposed for the controlled release of fusion energy, the stellarator uses a strong magnetic field for holding the heated hydrogen gas away from the walls. The unique and distinctive feature of the stellarator is the particular type of magnetic field which it utilizes. The hydrogen gas in the stellarator is placed in an endless tube, and the (longitudinal) magnetic field in the tube is produced by electric currents flowing in coils encircling the tube. A configuration of this sort must be rather complicated to assure confinement of the heated gas. One method involves the use of a tube bent into the form of a figure-eight, with simple circular coils encircling the tube and producing the magnetic field. In another method, the tube is doughnut shaped, but two types of external coils are required, an outer circular set, and an inner set of helically wound coils. This second method has the advantage that, like the stabilized pinch used at Los Alamos, at Berkeley, and in the British Zeta experiments, this type of configuration tends to be stable against certain types of magnetohydrodynamic disturbances.

In both these methods the magnetic field is characterized by "rotational transform." According to this property, a single magnetic line of force, if followed along the stellarator tube, does not close on itself, but gradually rotates around the central line of the tube. The rotational transform produced by the complex magnetic field of the stellarator plays a vital part in the operation of the device. Detailed theoretical studies show that a stellarator should be capable of confining an ionized gas for the length of time needed in a controlled thermonuclear reactor. The chief uncertainty in the theory is whether the heated gas will remain quiet and motionless under these conditions, as has been assumed. If turbulence, oscillations, and other types of unsteadiness appear, the magnetic field may not be sufficiently effective in confining the gas, which will cool off on contact with the wall.

Methods of heating the gas in a stellarator were also described by Spitzer. Two stages of heating appear to be necessary. In the first stage, the gas is heated up to about one million degrees, by means of an electric current flowing through the gas, in the same direction as the center line of the tube. In this ohmic heating process, the gas is heated by the flow of current in the same way that a wire is heated by a current flowing along it. To produce this current through the gas, an iron core may be used, encircling the tube, and current passed through an auxiliary winding around the core. The stellarator tube then forms the secondary of a transformer, and current is induced around the gas in this tube. Theoretical calculations on the rate of heating achieved in this way indicate that temperatures of about a million degrees should readily be achievable. At higher temperatures the resistance of the gas falls to such a low value that not much heating can be obtained with practical currents.

To achieve, in a stellarator, the 100,000,000° temperatures needed for a controlled thermonuclear reactor, the Princeton group plan to utilize a method called "magnetic pumping." This method consists in using a rapidly pulsating magnetic field in one section of the stellarator tube. The pulsation frequency is in the high radio range. The most heat is pumped into the gas if the pulsation period agrees with one of the natural periods of the gas—the time between collisions for a single particle, or the time required for a particle to pass through the magnetic pumping section.

To permit high temperatures, the gas in a thermonuclear reactor must be kept very pure, since impurities cool the gas by excessive radiation. To enhance the purity of gas in a stellarator an additional modification of the complex stellarator magnetic field, called a "divertor" is proposed. In one short section of the stellarator the

magnetic field in the outer regions of the tube is directed radially outwards, so as to guide the particles out of the discharge tube into a separate chamber. The purpose of the divertor is to ensure that any particles drifting slowly towards the tube wall will be guided into the divertor chamber before they strike the wall. Impurities liberated by collisions of these particles with the wall will then be confined to the divertor chamber, and will not readily make their way back into the main discharge tube.

Oak Ridge's DCX

The method being pursued at Oak Ridge National Laboratory provides for a beam of particles accelerated by a high-voltage source to be injected into a magnetic container for trapping.

The approach, first advanced by John S. Luce, is to accomplish this energetic injection and trapping through molecular breakup. This procedure calls for a high-energy 300-kev molecular deuterium ion beam to be injected across the magnetic field which serves to confine the ions.

The molecular ion is a charged system of two deuterium nuclei and an electron. Ordinarily, the molecule moves in a large circle within the magnetic field and returns to strike the source from which it is injected. However, the molecule can be dissociated into two particles: a singly-charged deuterium ion, and a neutral deuterium atom composed of the remaining deuterium nucleus and the electron.

After dissociation, the neutral atom flies out of the system because it no longer is contained by the magnetic field. The remaining ion, however, now circles in a new orbit half the radius of the original circle. Thus, if the dissociation is accomplished at the other edge of the molecular orbit, the resultant ion is trapped since it does not return to strike the source.

Dissociation is accomplished, with high efficiency, by passing molecular ions through an unusual type of electrical arc discharge discovered by Luce. The trapped ions circulate in a closed circle until they finally are lost from the system because of scattering or loss of energy.

The injection and trapping is into a magnetic mirror bottle, such as described by Post (below). This composite machine is known as DCX (direct current experiment). Note that the magnetic fields and injected current are not time varying.

This example has been greatly simplified, since it envisions trapped particles moving in a single organized ring current. Actually, these orbits will spread out because of energy loss and the nonuniform nature of the confining magnetic field. Trapped-particle paths will cross each other, and the desired nuclear reactions can then occur.

There are several competing actions undesirable to this scheme, one of which is charge exchange. If neutral gas atoms are in the plasma, an energetic ion can steal an electron from this atom and itself become electrically neutral. Because this energetic neutral atom is no longer confined by the field, it escapes. As a result, the inner system must initially be pumped down to very low gas pressures to prevent such an energy drain on the system. In addition, it may be necessary to utilize the trapped beam itself to further clean up residual gas in the container.

Another competing process to be controlled is energy loss to cold particles which may enter the system.

At Oak Ridge, research using the above-mentioned concepts has been underway for some time. Although the experimental and theoretical problems are difficult and involved, considerable progress has been made. Detailed reports of these results will be presented in the future.

Livermore's Mirror Machine

In its simplest form the mirror machine [also called the Pyrotron] consists of a long straight tube surrounded by a set of coils that produce a longitudinal magnetic field within. At either end of the tube the currents in the coils are made much stronger and the magnetic field is correspondingly stronger. Thus the pattern of field lines has the general aspect of an elongated football.

The hot plasma is confined in this football-shaped region. The uniform magnetic field in the middle of the machine keeps the plasma from escaping sidewise to the chamber walls. The "mirror" ends reflect particles back into the tube and give the device its name.

One of the major problems of the machine arises from the deflection of plasma particles. Normally particles move at right angles to and in a helical path along the magnetic lines of force. This permits the bunched lines at the end to reflect the particles back into the tube. However, the particles can be deflected by collisions with each other so as to travel straight along the magnetic field lines without spiraling; particles thus directed can easily escape through the mirrors.

One of several ways to combat this escape of particles is to make the particles very hot. This can be done by increasing the strength of the magnetic field starting from a low value. This then compresses the plasma near the middle of the machine and causes it to heat up. With the increase of temperature the rate of fusion increases and also fewer undesirable scatterings take place.

In some of the experiments magnetic field strength as high as 200,000 gauss (corresponding to pressures of ~30,000 psi) have been used. Heating effects from the squeezing of plasmas have been observed.

Stability of the confined plasma—one of the most elusive goals in fusion research—has thus far been observed in the mirror machine.

"However," Dr. Post cautions "while the research has been encouraging neither the experimental nor the theoretical work is yet far enough along to guarantee that a plasma of the size, pressure and temperature required to achieve practical amounts of power from fusion reactions would be stably contained in a simple mirror machine."

"The best hope for utilizing the simple mirror principle in producing a self-sustained reaction probably lies in operation at very high kinetic temperatures, perhaps $10^{9°}$ C or even higher" Dr. Post said. "At these temperatures, particles of the plasma can theoretically be reflected back and forth between mirrors for hundreds of thousands of times before being deflected by collision. Theoretical calculations indicate, however, that even at these temperatures the margin of energy gain compared with energy loss to escaping particles is not large. So that it would be very advantageous to employ additional means for reducing energy and particle loss. Such means are being studied and show promise on theoretical grounds."

BOOKS

An Introduction to Fluid Mechanics and Heat Transfer

By J. M. KAY (Cambridge University Press, New York, 1957, xvi + 309 pages, $7.00).

Reviewed by D. C. HAMILTON, Oak Ridge, Tennessee.

This small book is based on lectures given in the Imperial College of Science and Technology, University of London. The subject matter is less general than the title suggests. The book is more accurately described as an introduction to the fundamental principles of fluid mechanics and one specific heat-transfer phenomenon: single-phase forced convection in fluids (not including liquid metals). Brief chapters are also included on *Diffusion and Mass Transfer*, *Solid Particles in Fluid Flow*, *Flow Through Packed Beds and Fluidized Solids*, and *Condensation and Evaporation*.

The following is from the author's preface: "The object has been to cover the more important aspects of fluid flow and the transfer of heat and mass from the point of view of chemical and mechanical process engineering. The main emphasis is on the fundamental principles of fluid mechanics and heat transfer . . . "

From the viewpoint of an engineer educated in the United States, this is a most unusual combination of objectives to incorporate in a single book. Our introductory books written "from a point of view" are usually "applied" rather than "fundamental" in flavor. This book is most definitely in the latter category. The author has included only those topics that are, in his opinion, important to "process engineers." Accordingly, thermal radiation is omitted, and such topics as conduction, free convection, heat exchangers, boiling, condensing and convection in liquid metals are given only brief to superficial treatment.

Vector notation is used in the formulation of the basic differential equations, such as the Navier-Stokes equations of motion for a viscous fluid. These sections are too tersely written for the first reading. They are beautifully done, however, from the point of view of a reader who desires a review.

The book was designed for a highly specialized pedagogical purpose. For this reason, it is not as generally useful to engineers educated in the U. S. as most books of the same title.

An Introduction to Reactor Physics

By D. J. LITTLER and J. F. RAFFLE (Pergamon Press, New York, 1957, x + 208 pages, $5.50).

Reviewed by ARTHUR I. BERMAN, Rensselaer Polytechnic Institute, Hartford Graduate Div., E. Windsor Hill, Conn.

For the reader who does *not* intend to make the analysis of the physics of nuclear reactors his specialty, this book serves a particularly useful purpose in aiding in the completion of the second educational phase. It is a concise, analytical treatment of the elements of nuclear reactors, which a serious student of any branch of nuclear science and engineering ought to have as part of his background. The reactor theoretician, however, would find that the book barely scratches the surface of his storehouse of analytical information and technique.

Although the scope of this small volume is wide, it is marked by a clarity and ease of reading that provides good contact between author and reader, even though the latter's intimacy with higher mathematics may be limited. Here and there the author expects too much—for example, the calculation of a neutron's squared average distance of travel as a double summation of scalar products of vector displacements (p. 75) might require a few lines of explanation for the average reader for whom the book is intended.

Many of the introductory chapters on atomic and nuclear physics should be regarded as a review of material that the reader might well have studied previously. It is doubtful if anyone who lacks this background could gain more than a superficial understanding of these subjects from the wealth of ideas concentrated in these chapters. However, there are many sections in these introductory chapters that are far from superficial—the treatment of the binding energy of the liquid-drop model is one. The remaining chapters of the book are concerned with the elements of neutron diffusion, reactor critical size, calculation of lattice constants, pile kinetics and radiation interactions.

The effectiveness as a text is limited by the omission of assigned problems and dearth of worked-out examples. Aside from these objections the book would be a useful addition to the library of anyone who could benefit from a brief and well written introduction to the vast field.

Encyclopedia of Physics, Vol. 42, Nuclear Reactions III

Edited by S. FLÜGGE (Springer-Verlag, Berlin, 1957, vii + 626 pages, DM 135).

Reviewed by I. HALPERN, Department of Physics, University of Washington, Seattle, Wash.

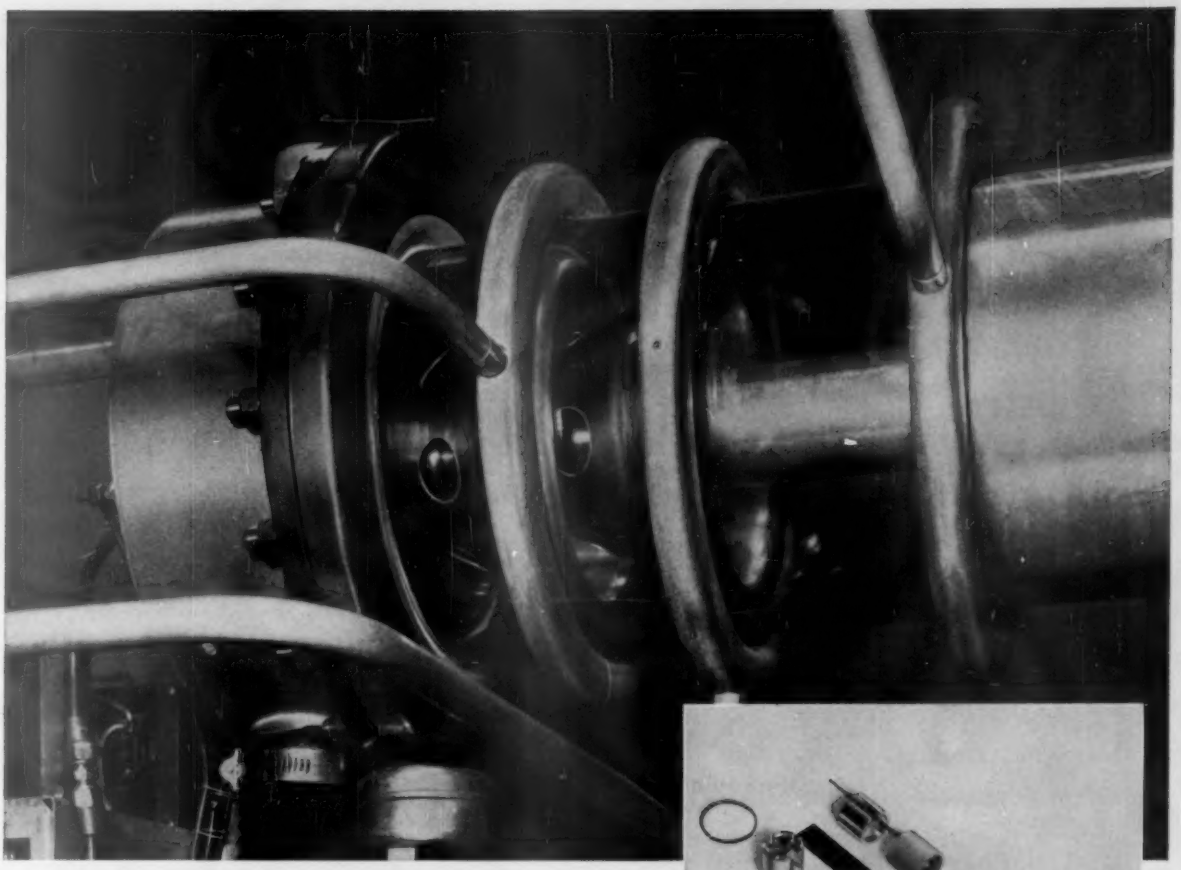
This book is one of the 54 volumes of the revived "Handbuch der Physik," which was originally published a generation ago. The subtitle of this particular volume, "Nuclear Reactions III," is unfortunately somewhat misleading. Most of the six articles in the book are concerned with problems of the decay of excited nuclei rather than with "reactions" as the term is usually used.

Two of the articles deal with nuclear properties of the heaviest nuclides. One is titled *Alpha Radioactivity* and the other *The Transuranium Elements*. In the first, I. Perlman and J. O. Rasmussen record the available data on decay energies and transition probabilities in alpha decay. They also discuss the recent developments in the theory of the transition probabilities.

The article on the transuranics, by E. K. Hyde and G. T. Seaborg, was written in a way that makes it a handy reference for the chemical and physical properties of these elements. The nuclear properties of the individual nuclides are also neatly recorded with the help of many diagrams and tables. For example, there are tables giving nuclear masses, slow-neutron capture and fission cross sections, etc.

The remaining two articles deal with the interpretation of nuclear experiments on the angular relationships of nuclei and their radiations. The longer article, by S. Devons and L. J. B. Goldfarb, is called simply *Angular Correlations*. Its organization is essentially theoretical, those topics being treated together for which the required mathematical formalisms are similar. The final article on *Oriented Nuclei* is by R. J. Blin-Stoyle and M. A. Grace. The authors describe a number of experiments that make use of the recently developed techniques for lining up the spins of an assembly of nuclei. In some of these experiments the nuclei are fixed in more or less ordinary matter. In others they are traveling to or from a nuclear reaction.

One can demand a great deal of something that calls itself an encyclopedia. It should, on the one hand,



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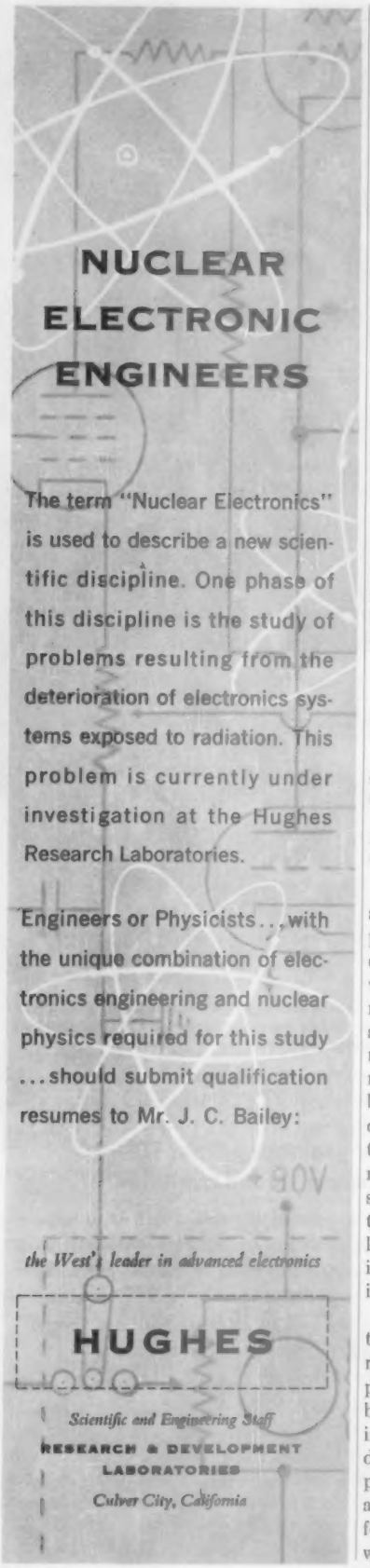
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The term "Nuclear Electronics" is used to describe a new scientific discipline. One phase of this discipline is the study of problems resulting from the deterioration of electronics systems exposed to radiation. This problem is currently under investigation at the Hughes Research Laboratories.
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serve as a good introduction for beginners to the various fields it treats; on the other hand, it should have sufficient detail to please the specialists. In short it should be both textbook and handbook. It seems to me that this volume is rather too much handbook. This is in part evident from the choice of titles. Each article covers a field in which there has been considerable activity since the war. The topics correspond much more to types of nuclear physicist than to chapter headings in a textbook seeking to develop the basic ideas of nuclear physics. The volume differs too little from the annual nuclear-physics review volumes that are published here and in England. It may not have the lasting quality that one expects of a good encyclopedia.

Nevertheless, it must be admitted that for the specialist working in fields related to those described, this book should prove to be extremely valuable.

Radiation Effects in Solids

By G. J. DIENES and G. H. VINEYARD (Interscience Publishers, New York, 1957, viii + 226 pages, $6.50).

Reviewed by J. H. KITTEL, Metallurgy Div., Argonne National Laboratory, Lemont, Ill.

This concise text will be a valuable addition to the library of the solid-state physicist, whether or not he is directly concerned with irradiation studies. It will also be of good use to reactor metallurgists and engineers who desire a better understanding, based on current thinking, of the fundamental mechanisms and theories that have been developed to account for the changes observed in matter subjected to irradiation. The book will not help, nor is it intended to, the reactor designer who must select fuel or structural materials, and whose choices are largely dictated by the magnitude of irradiation effects in the materials of interest.

The authors discuss in the first chapters the theory of the interaction of radiation with matter, displacement production, spike characteristics, and basic experiments that have provided insight to guide or confirm theoretical developments. Next, the nature and properties of defects are described, and, after discussing the annealing of defects, this portion of the text concludes with an interesting account of the procedures used and results obtained in annealing the graphite in the Brookhaven reactor. Because of the recent Windscale incident in the United Kingdom, this account takes on added interest. Finally, the authors conclude with a chapter on special topics, such as irradiation effects on mechanical properties of metals, irradiation growth of uranium, phase transformations, solid-state precipitation, etc. Most of the material in this chapter is discussed all too briefly, although the authors acknowledge that the topics are complex and cannot be treated in a simple way. However, should a future revised edition appear, it is to be hoped that this section, which considers the more challenging problems, will be given a more extended discussion.

It should be mentioned that the chapters are concluded with unusually extensive bibliographies, ranging from about 50 to over 100 references.

Soviet Education for Science and Technology

By ALEXANDER G. KOROL (Technology Press, Massachusetts Institute of Technology, and John Wiley & Sons, New York, 1957, xxv + 513 pages, $8.50).

Reviewed by CALVIN POTTS, U. S. Atomic Energy Commission, Washington, D. C.

Anyone writing on Soviet education is faced with difficulties arising from the existence of the Iron Curtain. His sources of information are relatively limited, comprising for the most part Soviet periodicals and a few official documents; information from people who were educated in Russia, but no longer resident there; and information from people who have visited Russia in the last few years, but who have probably only seen those particular things that the Russians wished them to see.

Mr. Korol has many factors in his favor. Now a U. S. citizen, he was born in Russia and received much of his education there. He left Russia in 1920 and completed his education in the U. S. In recent years, he has played a part in the Harvard Refugee Interview Project and has been on the research staff at the Center for International Studies at Massachusetts Institute of Technology. This background, plus an extensive study of such periodical and documentary literature as exists, has provided Mr. Korol with a good background for writing "Soviet Education for Science and Technology."

The first eleven chapters, which com-

prise the bulk of the book, are devoted to the exposition of the facts of the Russian educational and training system. Mr. Korol's discussion includes the 10-year school, technical schools, university curricula, textbooks and qualifications of teachers. Although there are many tables of data and much factual material about Russian education, Mr. Korol has endeavored, quite successfully, to develop this into a coherent background.

The most important part of the book is chapter 12 entitled "Comments and Reflections" in which Mr. Korol comments on and highlights the preceding text. He points out: "The rationale and aims of Soviet education inevitably reflect the basic Communist view of society and the place the individual occupies in it."

The four foundation facts of Soviet educational systems are: (1) the prescription of *national maximum* admissions quotas; (2) the assurance that all designated vacancies are filled; (3) the dictatorship's capacity to adjust to changing circumstances and needs by decree; and (4) the unmodified ends of Soviet education since the inception of the regime 40 years ago.

Because of the difference in aims, direct comparison of the U. S. S. R. and U. S. educational systems is most difficult. It should be recognized for what it is—the attempted comparison of facets from two quite different cultures. Mr. Korol's dual background has enabled him to avoid the usual pitfall of interpreting U. S. S. R. education in terms of U. S. aims and customs. He states: "We cannot emphasize too strongly, then, that if we are seeking for the deeper meanings of the nature of the Soviet educational system as set against our own, if we are seeking to find in a comparison of the two systems a measure of the challenge which confronts American education, then our comparison must be set in the broad context of communist and democratic objectives in their widest sense."

Atomic Energy in Agriculture

By WILLIAM E. DICK (Philosophical Library, New York, 1957, x + 150 pages, $6.00).

Reviewed by L. E. BROWNELL, Fission Products Laboratory, The University of Michigan, Ann Arbor, Mich.

This book was prepared for the *general* scientific reader by an author with experience as an editor of chemical journals and as a research biologist. The style is that of the popular press rather than the formal style of the scientific writer. The approach is similar to that of the old professor who reviews some new developments for the benefit of a lay audience having some background in general science. The first person is used throughout and the style is often of conversational nature. One suspects that much of the text was written by oral dictation.

The book is based primarily on papers presented at the 1955 Geneva Conference and contains six chapters, the first of which is entitled *Remaking Crop Plants with Radiation*. This chapter deals, of course, with the production of mutants with the aid of radiation. A considerable portion of the early part of the chapter is devoted to a general discussion of genetics that is necessary if a reader not familiar with the subject is to understand this use of radiation. The chapter makes interesting reading if one is not familar with the field and is slightly more technical than an article on this subject might be if found in "Reader's Digest."

The second chapter, entitled *Photosynthesis Tracing the Path of Carbon with Radio-Isotopes*, is too short to cover the subject adequately. The reader is introduced to the subject and then shown some illustrations of the complete photosynthetic carbon cycle, chromatograms and a diagram showing the "Krebs" cycle. These are not sufficiently explained to be understood by a reader not familiar with biochemistry.

Chapter 3, *The Path of Other Elements*, is perhaps the most interesting chapter in the book. The author spends a number of pages discussing the pioneer work of G. deHevesy in developing the tracer technique. Many articles have been written on the subject of tracers but usually little or no mention is made of the interesting story of the development of this powerful analytical tool. On the other hand, the chapter does not include much information on the "path of other elements" except for phosphorus. A brief discussion is presented of the interesting application of nutrients in foliar sprays.

Chapter 4, *Radioactive Materials in the Fight against Pests*, is also a rather interesting chapter. The author discusses tracer techniques in investigations of the habits of insect pests and briefly describes the very interesting experiment with the screw-worm fly on the island of Curacas. In reviewing the use of tracers in studies of the

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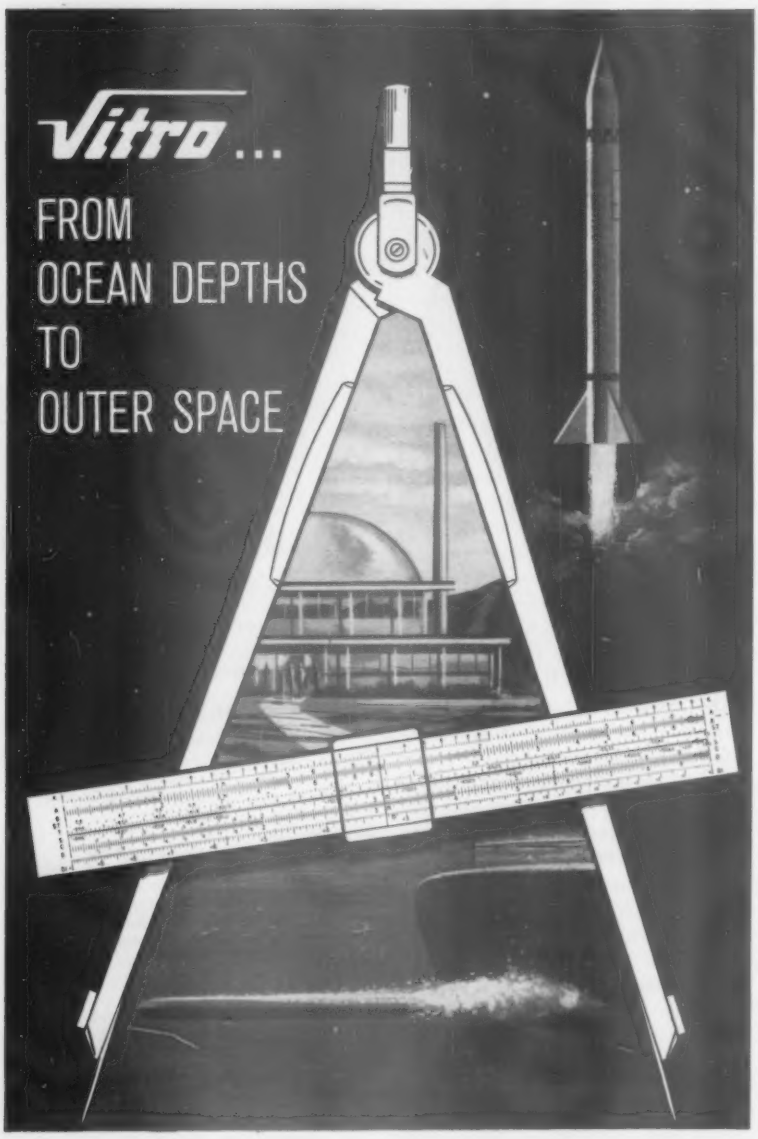

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- Ceramic colors, pigments, and chemicals

action of insecticides, the author gives a brief discussion including illustrations of the principle of the chromatograph. Three pages are also devoted to a review of the direct use of radiation to kill insects in cereals and other agricultural products.

Chapter 5, *Radioactive Tracers and Forestry*, is short (10 pages) and is devoted primarily to a review of tracer studies on graft unions in roots of trees and on the spread of fungus disease through root grafts. This is probably the least interesting chapter to readers not particularly concerned about these problems in forestry.

The final chapter, *Atomic Radiation and Food Preservation*, is one of the longer chapters. It begins with a good discussion of the problem of disposal of the waste fission products. This is followed by a review of the early studies by Proctor, Huber and Hannan on preservation of food with ionizing radiation. The effects of radiation on various biological systems, the question of possible induced radioactivity and the problem of flavor change are discussed. The author makes a mistake in listing sterilizing doses for various types of food (Table 8) since it is now known that much larger doses are necessary.

In conclusion I believe it can be said that the book is an entertaining review of selected studies on applications of nuclear radiations in the field of agriculture and agricultural products.

BOOKS RECEIVED

Ionization and Breakdown in Gases, by F. Llewellyn-Jones (John Wiley & Sons, New York, 1957, 176 pages, $3.50). One of Methuen's Physical Monographs, this book for the post-graduate research worker gives the fundamental physics of electrical breakdown of gases and recent work in the field. It also shows where further data are needed.

Advances in Electronics and Electron Physics, Vol. 9, edited by L. Marton (Academic Press, New York, 1957, x + 347 pages, $9.00). In the spirit of the International Geophysical Year, the editors have adopted a geophysical theme for this volume. Contributions cover cosmic phenomena, radiowave propagation, oceanography, seismology and geomagnetism.

LETTERS

Materials Witnesses

DEAR SIR:

In the article "What Price Nuclear Materials?" by Malcolm F. Judkins (NU, Jan. '58, p. 96) were included, in the list of shielding materials, two items: lead shot, for which was given a cost of 30¢/lb, and lead sheet, at a cost of 75¢/lb.

It would be more accurate if the shot were shown at 18¢/lb and sheet at 18.5¢/lb. These are quantity prices f.o.b. point of shipment.

—LESTER N. LUKKASON
National Lead Company
New York, N. Y.

DEAR SIR:

I find that I must disagree with part of the section concerning niobium in the report "What Price Reactor Materials?"

The points questioned are these: (1) niobium supply—actually both niobium minerals and niobium metal are presently in need of greater markets. (2) Nigerian sources—in 1956–7, only about 60% of imported ores came from Nigeria, not 95%. (3) Outlook for increased supply—this is not unfavorable. Ore reserves have been increased tremendously in the past few years. Increased production awaits only increased markets. (4) AEC requirements—these estimates are really pretty much guesswork, and the 1957 figure should be 15,000 lb, not 30,000 lb.

I offer these comments in a spirit of mutual aid and hope that they are of interest to you.

—WILLIAM R. BARTON
Branch of Rare and Precious Metals
Bureau of Mines
U. S. Department of the Interior
Washington, D. C.

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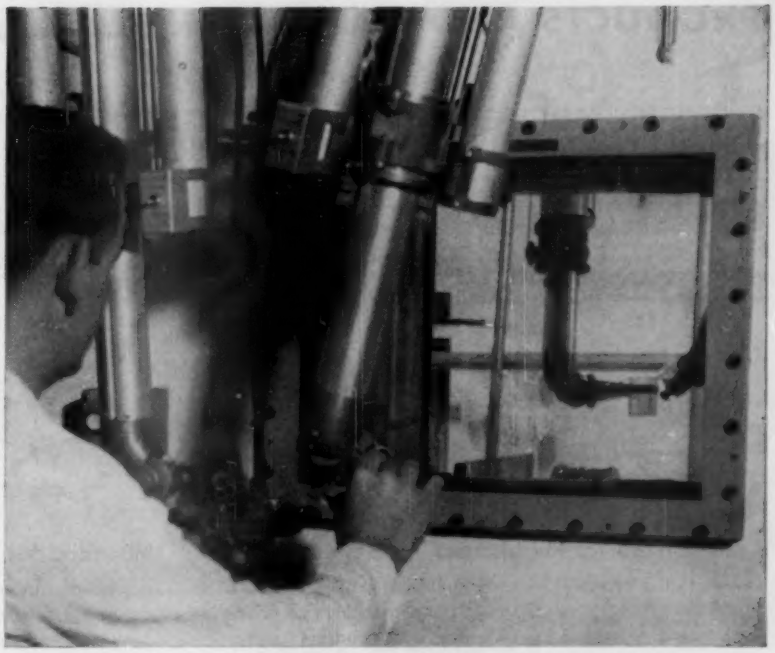


One of two 4½ foot thick radiation shielding windows Continental Oil Company has in its new hot cell. Hot cell walls are 5½ feet thick. Corning engineered and built the windows ready to install.

What happens when a new hot lab goes window-shopping

If you're building a lab for atomic research, most likely there's a hole in your plans—right in the hot cell wall.

Here's how Continental Oil Company found the shielding window *just right* to fill the hole, and how Corning helped them do it.

First Conoco specified the wall thickness, the energy level, and the desired viewing area of their new hot cell to Corning engineers. They emphasized that they wanted *protection;* yet they did not want to sacrifice *visibility*.

Then Corning engineering took over.

1. We determined size of the window in respect to the viewing area—kept size at a practical minimum. No extra glass, no extra cost.

2. We decided which glasses to use—whether to use one, two, or three of the *special* glasses we've developed to do the job. Corning glasses give maximum visibility.

3. We determined thickness to give Conoco the safety they wanted. Corning Code 8362 glass was included—it gives more shielding per dollar than any other glass.

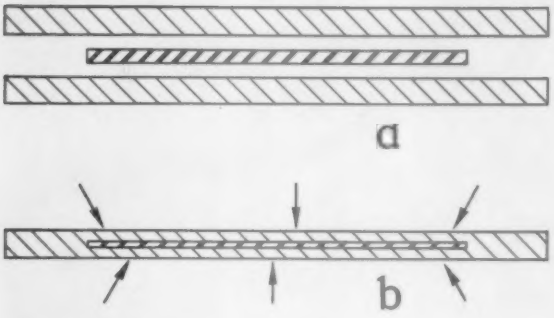
4. And finally, we built the window and delivered it *ready to install.*

Conoco got all they wanted . . . and then some. They had a window that was clear as crystal, that gave them maximum protection, and that was, in addition, resistant to radiation darkening and was self-recovering. And, Corning's skill with glass has developed a *permanent* glass that poses no periodic renewing or replacement problems.

To find out more write for a copy of Corning Bulletin PE-51, "Corning Radiation Shielding Windows."

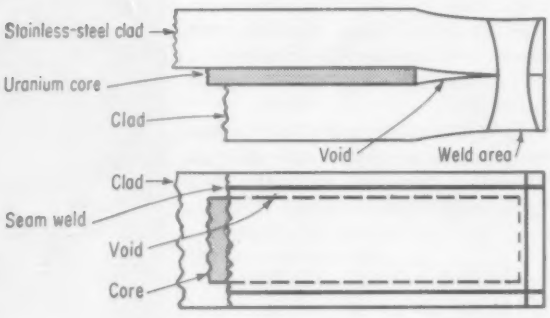
CORNING GLASS WORKS
16-5 Crystal Street, Corning, N.Y.
Corning means research in Glass

Fuel Strips for Critical Experiments



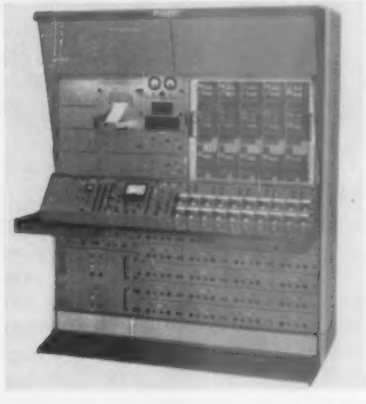
Cold-Bonded for Ruggedness

Cold-bonded critical-assembly fuel strips offer complete protection at lower cost than hot-bonded elements. Three basic steps comprise the patented cold-bonding process: cleaning the mating surfaces with high-speed wire brushes in a controlled atmosphere; single-pass reduction to form a "green" bond; heat treating to convert this temporary bond into a strong permanent one that is the equal of conventional hot-cladded solid-phase bonds. As shown in the figure above, the core is completely framed by cladding material. Subsequent rolling operations can bring the bonded strip to the required thickness with a minimum of distortion at the ends of the uranium core. Available in aluminum, zirconium and their alloys.—M & C Nuclear, Inc., P. O. Box 898, Attleboro, Mass.



Unbonded for Reprocessing Ease

Unbonded, but clad, fuel strips offer the advantage of economical fabrication and reprocessing while providing adequate heat transfer and integrity. As shown in the figure, intimate contact between the three mated components is attained by welding the cladding plates around the uranium core under vacuum. Atmospheric pressure then serves to press the cladding against the foil, assuring good heat transfer. A small void space is left at the end of the core but this is less than 5% of the theoretical volume. Suitable uranium foil for the core and stainless steel for the clad can be ordered to specification. Note that the uranium core can be relatively easily removed for reprocessing simply by stripping it of its cladding.—The Martin Co., Baltimore, Md.



Analog Computer

Model 231-R (above) has modular grouping of components that eliminates patch board clutter and makes patching quicker. The patch board has 3,450 holes and is so designed that it facilitates increased use of bottle plugs and shorter patch cords. The board is capable of terminating 100 operational amplifiers and associated nonlinear equipment. The 231-R also provides advances in speed of operation with automatic extended readout, which permits the entire system to be scanned, and values printed, at the rate of 200 points per min, and all-electronic digital voltmeter and potentiometer settings.—Electronic Associates, Inc., Long Branch, N. J.

Air Impinger Apparatus

This is an all glass device used to collect radioactive particles or dust from air for subsequent analysis. It will collect all particles larger than 0.5 microns.—Gelman Instrument Co., 233 Jefferson St., Chelsea, Mich.

Pressure Switch

Model 575-370 has heliarc welded seams and operates at up to 10,000 psi. The sensing member has no gaskets, O-rings, or sliding seal and maintains its performance characteristics and calibration at 1,000° F and radiation levels of 1.2×10^9 r of gammas and 3.73×10^{17} n/cm² (total).—Diaphlex Div., Cook Electric Co., 2700 Southport Ave., Chicago, Ill.

Digital Recorder

Model 560A (above) is a fast digital recorder that prints 11 columns of information at up to five prints per sec. Although primarily designed to make a permanent record of electronic counter read-outs, the 560A can be used with two or more digital voltmeters, time recorders or flowmeters simultaneously. In addition to the printed tape record, the 560A provides an analog current or voltage output to drive a galvanometer or potentiometer strip chart recorder or to provide servo control.—Hewlett-Packard Co., 275 Page Mill Rd., Palo Alto, Calif.

Radio-Survey Meter

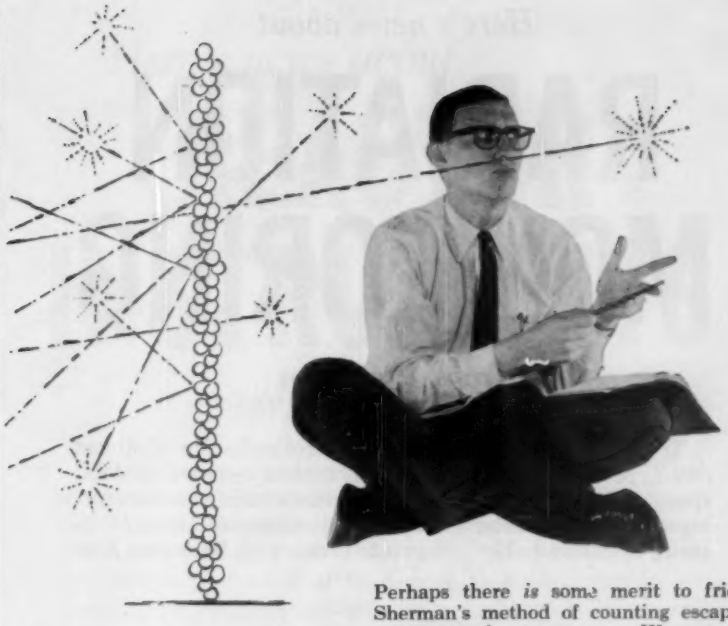
Model P-1R (above) combines small, lightweight gamma-radiation detector with standard transistorized radio receiver. General specifications are as follows: high-sensitivity detection from background to 100 r/hr, logarithmic scales and self-contained ionization chamber powered with mercury battery capable of at least one-year operation.—Riggs Nucleonics Co., 1699 E. Mendocino Ave., Altadena, Calif.

Wide-Band Amplifier

Model 600 high-gain, wide-band amplifier has specifications as follows: bandpass, 200 cps–50 Mc; gain, 40 ± 1½ db (into matched load); rise time, 10 mμsec; maximum pulse duration (10% droop), 60 μsec; pulse delay time, 20 mμsec; recovery time (100 times overload), 500 mμsec; noise figure, ~9 db; gain-control range, 20 db; linear range at full gain, ~60 db.—Instruments for Industry, Inc., 150 Glen Cove Rd., Mineola, N. Y.

Automatic Welding Torch

Torch and control system (above), designed to meet the most critical standards of thin-gage nuclear fuel-element welding, has replaceable torch head, rack-and-pinion mounted, with adjustable cam-follower guides. Two standard voltage-regulated gear-head motors drive torch head with standard high-sensitivity electronic control. Specifi-



it's the little things that count

Perhaps there *is* some merit to friend Sherman's method of counting escaping neutron and gamma rays. We are certainly not going to scoff at what may well be experimental originality in the field of nuclear research. However, we opine that Sherm's calculations are a bit too extreme. Accuracy might better be achieved by one of our DETECTOLAB* Nuclear Systems.

The people at one of America's great nuclear research centers agree. That's why reliable DETECTOLAB instrumentation has been selected for their new shielding research area. The open-tank pool type facility is to study the shielding properties of materials and configurations exposed to radiation resulting from fission of U-235.

Fast neutron and gamma radiation measurement involves DETECTOLAB proton recoil and multiple-crystal gamma ray spectrometers plus instrumentation to indicate pool and source-plate temperature, pool radioactivity, bridge and tower positions, boral curtain position and fission plate power. Indication and control will be from a central console.

Our capability to perform well and within budget on such interesting applications is widely recognized. Write for our Application Report and a new short form catalog that lists and describes the more standard off-the-shelf DETECTOLAB Nuclear Instruments. We would leap at the opportunity to discuss those, or more unique products, should you care to inquire.

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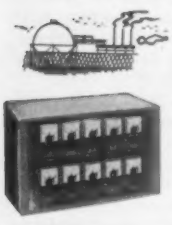
Here's news about

RADIATION MONITORING

from Victoreen

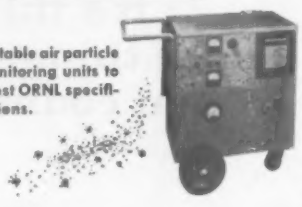
To detect, measure, record or control radiation of almost any type or intensity . . . with complete systems to AEC specifications—that's *part* of Victoreen's radiation monitoring story. So no matter what your radiation monitoring problem, it will probably pay you to check with Victoreen *first.*

area monitoring



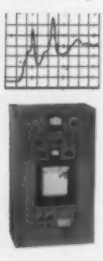
Flexible, fully proven remote area systems to AEC requirements for radiation monitoring from a single control center.

air particle monitoring



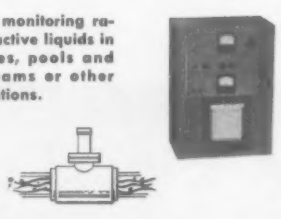
Portable air particle monitoring units to latest ORNL specifications.

fission products monitors



A reliable monitoring system based on MTR design at Idaho Falls for detection of fission product activity in coolant stream.

water monitors



For monitoring radioactive liquids in pipes, pools and streams or other locations.

neutron monitors

Fast and thermal neutron monitoring systems designed for bulk shielding and dosimetry studies.

gas monitors

Designed for continuous monitoring of radioactive stack gases. Contains built-in alarm system to operate external control circuits.

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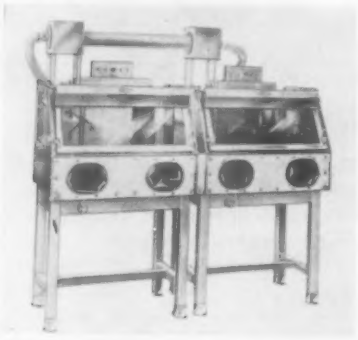
cations are: electrode sizes, 0.040–0.25 in.; maximum current, 600 amp; maximum rate of vertical travel, 60 in./min; maximum rate of horizontal travel, 32 in./min. High-frequency arc starting can be used.—Vacuum Specialties Co., Inc., 34 Linden St., Somerville, Mass.

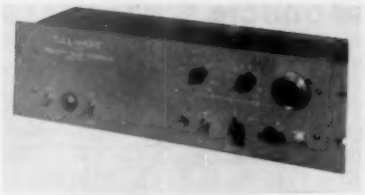


Glove Box

All-purpose stainless-steel safety enclosure (above) features modular construction. Basic unit is 36½ in. long, 24 in. high and 28 in. deep and is fabricated from polished type-304 stainless steel. Hinged safety-glass window has Neoprene gasket to provide the required close fit and tightness. Each unit has 5-in. cup sink fabricated as part of bottom tray.—S. Blickman, Inc., 8400 Gregory Ave., Weehawken, N. J.

Plug-In Scaler-Ratemeter

Model PFA-100 (above) can have pulse amplifier or linear amplifier and single-channel analyzer as input section. Counting unit can be either high-speed decade scaler (choice of 100 kc or 1 Mc) or wide-range ratemeter with aural monitor. Instrument includes built-in timer, continuously variable voltage for probe with 0.5% regulation 500–2,500 v, self-contained calibrator and connection for 1-ma pen recorder.—Nuclear Electronics Corp., 2632 W. Cumberland St., Philadelphia 32, Pa.

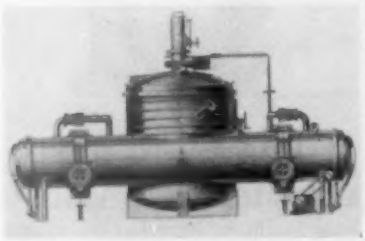


Pulse Generator

Model PPG-256 precision pulse generator (above) uses mercury relay for generation of positive or negative pulses that simulate output of most radiation detectors for testing and calibration of multichannel pulse height analyzers.—Tullamore Electronics Laboratory, 605 S. Ashland Ave., Chicago 36, Ill.

Footwear Decontaminating Bath

Ultrasonic footwear decontaminator (above) consists of tank fitted with treadle to support weight of user. Circulation of fresh water to level of 1 in. above soles is provided. Optional automatic metering device adds appropriate detergent to bath periodically.—Acoustica Associates, Inc., 26 Windsor Ave., Mineola, L. I., N. Y.



Vacuum-Casting Furnace

Four-chamber furnace (above) features mold tunnel for continuous direct casting of shapes or ingots under inert-gas atmosphere or vacuum. Its capacity is up to 5,000 lb. Vacuum lock system permits insertion or removal of molds without breaking vacuum in main furnace chamber. Automatic in-

Here's news about

REACTOR INSTRUMENTS

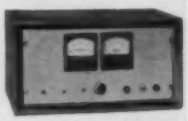
from Victoreen

Reliable, accurate reactor instruments for use as individual components in "customized" systems . . . reactor instruments to ORNL specifications, or to your own specialized designs—that's only *part* of Victoreen's story. Perhaps best of all is that we're in production and can ship all these and many other types. Bring your reactor instrument problems to Victoreen, the *specialists in reactor instruments and instrumentation.*

SIGMA AMPLIFIER

Model 676 Sigma Amplifier (ORNL Spec. Q-947). A safety instrument for reactor control which receives and transfers output of Period Amplifier to Magnet Amplifiers; monitors neutron or power level of the reactor.

LOG N AMPLIFIER

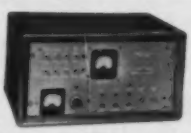


Model 677 Log N Amplifier (ORNL Spec. Q-915) indicates power level of reactor. Indicates negative reactor periods, infinity to 30 seconds, and positive reactor periods, infinity to 3 seconds. Supplies signal (logarithm of power level) to Period Amplifier.

PERIOD AMPLIFIER

Model 678 Period Amplifier (ORNL Spec. Q-1093). Used between Log N Amplifier and Sigma Amplifier; shuts down reactor and warns operator when power or neutron level of reactor increases at too great a rate.

COMPOSITE SAFETY AMPLIFIER



Model 738 Composite Safety Amplifier (ORNL Spec. Q-1565) combines Period, Sigma, and Magnet Amplifiers on one chassis, saving panel space and requiring fewer power supplies.

COMPENSATED IONIZATION CHAMBER POWER SUPPLY

Model 737 Compensated Ionization Chamber Power Supply (ORNL Spec. Q-995) supplies 600 volts, positive, and adjustable 75 to 350 volts, negative, to chamber, with fail-safe alarm for positive voltage supply.

MAGNET AMPLIFIER

Model 674 Magnet Amplifier (ORNL Spec. Q-889) supplies current to electromagnets that support shim and safety rods; receives signal from Sigma Amplifier when power level is too high and drops rods to shut down the reactor.

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Cary / instrument abstracts

Applied Physics Corp./362 W. Colorado Street/Pasadena/California

at the Richfield Laboratories

Cary Model 14 Spectrophotometer enables determination of lead concentrations to one part per billion

The destructive effect of lead on the activity of costly catalysts makes accurate determinations of even minute amounts extremely important. With improved techniques now in use at the new Research Laboratories of the Richfield Oil Corporation, Anaheim, California, chemists can determine lead concentrations in naptha charge stocks within one part per billion.

The conventional dithizone colorimetric procedures can be used to estimate the lead concentration to an accuracy of approximately 10 parts per billion. A refinement of this procedure, employing the Cary Model 14 Recording Spectrophotometer, is used to more precisely determine the concentration.

The color intensity of the lead dithizone solution is measured at 5100 Angstroms for the unknown sample and for two standard solutions whose concentrations are respectively a little more and a little less than the estimated concentration of the unknown. By interpolating, the analyst can then determine the lead concentration of the unknown to an accuracy of one part per billion or better.

In this procedure, the high photometric accuracy of the Model 14 is of primary importance in reliably recording the minute differences in absorbance values between the sample and standards. This high photometric accuracy is one of several performance features provided in each Cary Recording Spectrophotometer to a degree not found in any other similar instruments. Perhaps these advantages can lead to new breakthroughs in your analytical techniques. Complete information on both Cary Spectrophotometers, Model 11 and Model 14, is contained in a bulletin which is available upon request. Ask for Data File K10-58

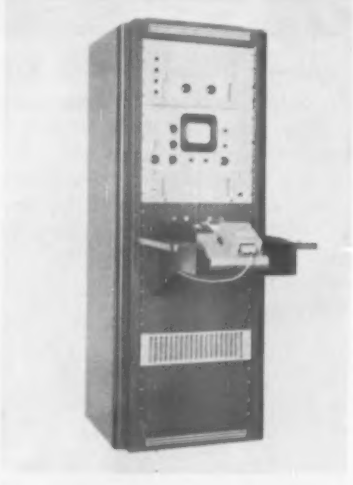
BRIEF SPECIFICATIONS OF CARY SPECTROPHOTOMETERS

	MODEL 11	MODEL 14
RANGE	2100Å to 8000Å	1860Å to 2.6 microns.
STRAY LIGHT	Less than 0.0001% over most of working range.	Less than 0.0001% between 2100Å and 1.8 microns; less than 0.1% at 1860Å and 2.6 microns.
SCANNING SPEEDS	From 1.0Å/sec. to 125Å/sec.	From 0.5Å/sec to 500Å/sec.
RESOLUTION	Better than 1.0Å throughout range.	Better than 1.0Å U.V.-visible region and 3.0Å near-infrared.
WAVELENGTH ACCURACY	Better than 5.0Å U.V. region and 10.0Å visible region.	Better than 4.0Å throughout range.
REPRODUCIBILITY	Better than 0.5Å U.V. region and 3.0Å visible region.	0.5Å throughout range.
PHOTOMETRIC REPRODUCIBILITY	0.004 in absorbance.	0.002 in absorbance.

dexing conveyor moves mold carts from entrance lock to tilt-pouring position in furnace.—Kinney Mfg. Div., The New York Air Brake Co., 3529 Washington St., Boston 30, Mass.

Impact Extrusions

Some interesting and unusual shapes produced by impact extrusions are shown above. Impacts are rapidly replacing many machined parts because of lower cost and simplified production. Very close tolerances are possible with more uniform wall thickness and virtually no draft. Extrusion impacts, produced in both aluminum and zinc alloys are seamless, jointless and have bright surfaces.—Impact Extrusion Products, Inc., 39 Powerhouse Road, Roslyn Heights, N. Y.



Pulse-Height Analyzer

Model PA-100 (above) 100-channel pulse-height analyzer features quartz-delay-line data storage originally developed by Hutchinson and Scarrott. Printer records readout data (both channel number and pulse counts) decimally on paper tape. Channel widths are 1 or 0.2 v. Capacity is 10^5 counts per channel. Over-all average dead time is 510 μsec.—Technical Measurement Corp., 140 State St., New Haven, Conn.

Medical Spectrometer

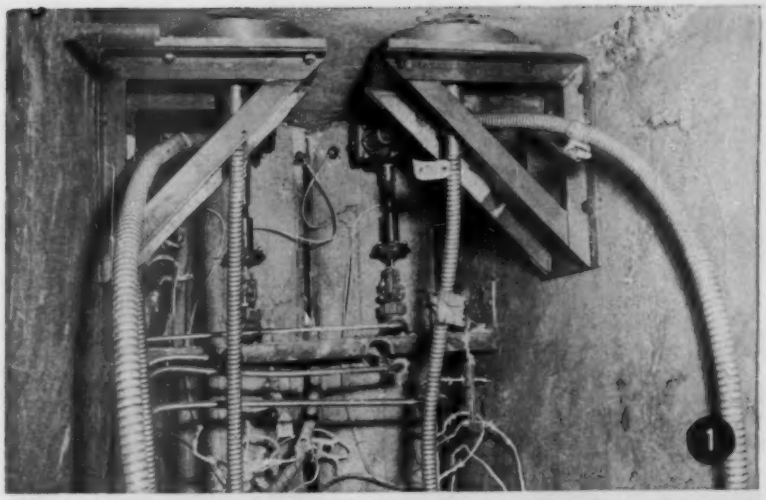
Model C-2600 (above) is mobile unit designed to provide high counting accuracy with minimum patient dosage. The unit consists of Model C-2910 single-chassis spectrometer, scintillation probe with sensitive 2 × 2-in. NaI crystal and console housing with counter-balanced, "fold-a-way" detector holder.—NRD Instrument Co., 9842 Manchester Rd., St. Louis 19, Mo.

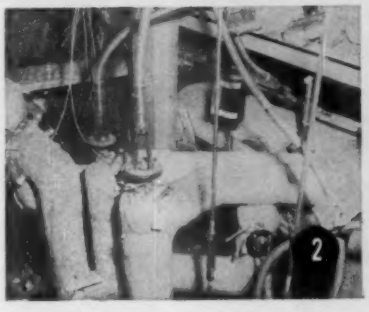
Self-Sealing Coupling

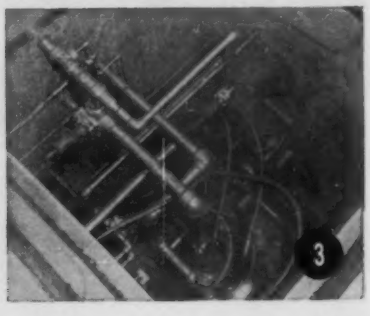
A coupling that will eliminate costly and dangerous spillage as the hose is connected and disconnected, it is both simple and efficient. Each of the two halves of the coupling contains a spring-loaded valve. One half is mounted on the tank or other receptacle and the other on the hose. The act of coupling and uncoupling, done simply by turning the wing nut, starts or stops the flow, even under pressure. Teflon hose and stainless-steel and aluminum fittings are also available.—Aeroquip Corp., 300 South East Ave., Jackson, Mich.

Reactor Simulator

Inexpensive reactor simulator provides all the characteristics of a nuclear reactor under variable operating conditions. Designed as a training tool, the 24 ft³ simulator comprises three computing sections: excess reactivity, nuclear power and heat transfer. A significant feature of the simulator is the incorporation of a mass flow control to demonstrate the power dependency of the reactor on coolant mass flow. The position of the control







MANUAL REMOTE VALVE CONTROLS

Stow Flexible Shafts Used in Sodium Reactor Experiment

Photo 1) Two half-inch globe valves located in the center of this photo are controlled by STOW size 40 geared joints connected by STOW flexible shafts. The flexible shafts go through the 6-foot concrete walls and are connected to valve remote operating terminals on the other side. Flexible shafts are used to operate these valves since they can be put in an "S"-shaped path when going through the concrete walls. This prevents radiation escaping from the chamber. These half-inch globe valves are used in the organic cooling system of the Sodium Reactor Experiment, an experimental nuclear power reactor built and operated for the Atomic Energy Commission by Atomics International, a division of North American Aviation, Inc.

Photo 2) STOW remote control flexible shafts control one-inch bellows seal valves, using STOW V2 valve couplings (center of photo). These are installed in the sodium service lines in the main gallery of the Sodium Reactor Experiment. The sodium system comprises equipment for melting, filtering and introducing sodium to the fill tanks. The half-inch globe valve at upper right is an inert gas line.

Photo 3) STOW flexible shafts control these 1-½ inch diaphragm valves in the radioactive waste vault of the Sodium Reactor Experiment. The liquid waste disposal system is designed to dispose of the effluent from the fuel cleaning cells and the hot cells.

For complete information on these controls, write today for Design Manual 553.

STOW MANUFACTURING CO.

355 Shear St., Binghamton, N. Y.

rods can be varied transiently, or by a fine manual control, or can be set to move at a required velocity. Delayed-neutron networks, appropriate to the fuels selected, are set by the SELECT FUEL potentiometers on the control panel. Trip circuits have been incorporated to simulate shutdown at a preset level or at some defined rate of increase of power level.—English Electric Co., Ltd., London, England.

Automatic Scanning System

Actigraph II (above) scans, counts, and records radio chromatograms automatically permitting easy location and quantitative measurement of all radioactive zones. System includes Model C100A strip feeder, choice of window or windowless radiation detectors mounted in lead shield for background reduction, count rate meter and chart recorder. Any paper width from ¼ to 1½ in. can be used. Rate of progress of the chart and the strip chromatogram is synchronized at any of ten different and constant speeds ranging from ¾ in./hr to 12 in./min.—Nuclear-Chicago Corp., 229 W. Erie St., Chicago 10, Ill.

Powder-to-Strip Mill

Model TAH-625 (above) is horizontal rolling mill that compacts metal pow-

N. WOOD RADIOACTIVITY DETECTORS

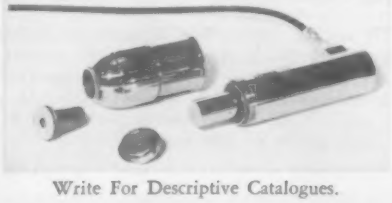
Shown here are a variety of neutron and cosmic ray counters featuring a 36″ long counter ½″ in dia. and our micro-neutron counter with 3/16″ x ¾″ active volume. Other counters range in size from ½″ dia. x 2½″ active length to 2″ dia. x 38″ active length and are filled at various pressures from 12 cm. to 120 cm. They are made of brass or aluminum and are fitted with 82–805 teflon connectors. They are used with standard commercial type scalers with one millivolt input sensitivity.

The display includes the 1½″ x 34″ active G-15-34A neutron counter now used in cosmic ray installations and in I G Y research all over the world.

Also shown is the new 2″ x 40″ cosmic ray proportional counter, which like the neutron counter has almost unlimited life.

We have a complete line of glass-wall counters including thin wall jacketed counters and bismuth cathode counters.

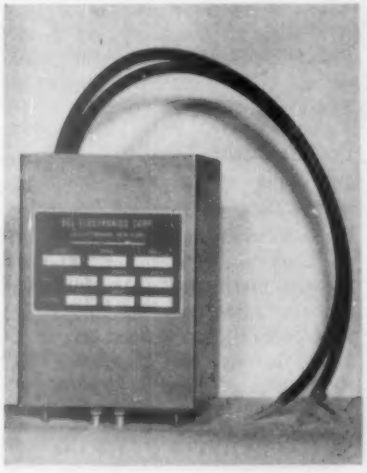
Our Scintillation counters include the SC-1U Universal counter shown below which takes interchangeable alpha, beta, fast and slow neutron crystals as well as gamma crystals of various sizes including the well-type.



Write For Descriptive Catalogues.

N. Wood Counter Laboratory
RADIOACTIVITY DETECTORS
1525 E. 53rd St., CHICAGO 15, ILLINOIS, Tel. FAirfax 4-1114

ders directly into sheet and strip and also is convertible to vertical 2-high/4-high combination mill. Mill is equipped with 8 × 8-in. rolls that produce materials in widths of up to 7 in. and thicknesses of 1.32–1.8 in., depending on metal powder being processed. Both wider and larger diameter rolls can be substituted to produce sheet widths of up to 11 in. and thicknesses in excess of ½ in. The mill can be used for both hot and cold rolling operations by using high-temperature-resistant rolls equipped with heaters.—Stanat Manufacturing Co., Inc., 500 Shames Dr., Westbury, N. Y.



High-Voltage Supply

Model 10-1-1 (above) will deliver 10 kv d-c at 1.25 ma with rms ripple of 0.25% at 60 cps or 0.04% at 400 cps.—Del Electronics Corp., 521 Homestead Ave., Mount Vernon, N. Y.

Co^{60} Irradiator

Model 1010 will safely contain up to 3,000 curies of Co^{60} in the standard source capsule provided by AEC and Atomic Energy of Canada Ltd. It has a fixed beam and distance and large fields (up to 28 × 28 cm at 50 cm and up to 40 × 40 cm at 70 cm) and three stages of collimation to assure <5% penumbra beyond the field.—Bar-Ray Products, Inc., 209 25th St., Brooklyn 32, N. Y.

Scaler-Analyzer

The RCLiac-32 consists of six "plug-in" modules as follows: number generator (32 eight-digit numbers) and cathode-ray tube display (31 points); magnetic core memory (10^6 counts per channel); power supply (well-regulated, positive or negative, continu-

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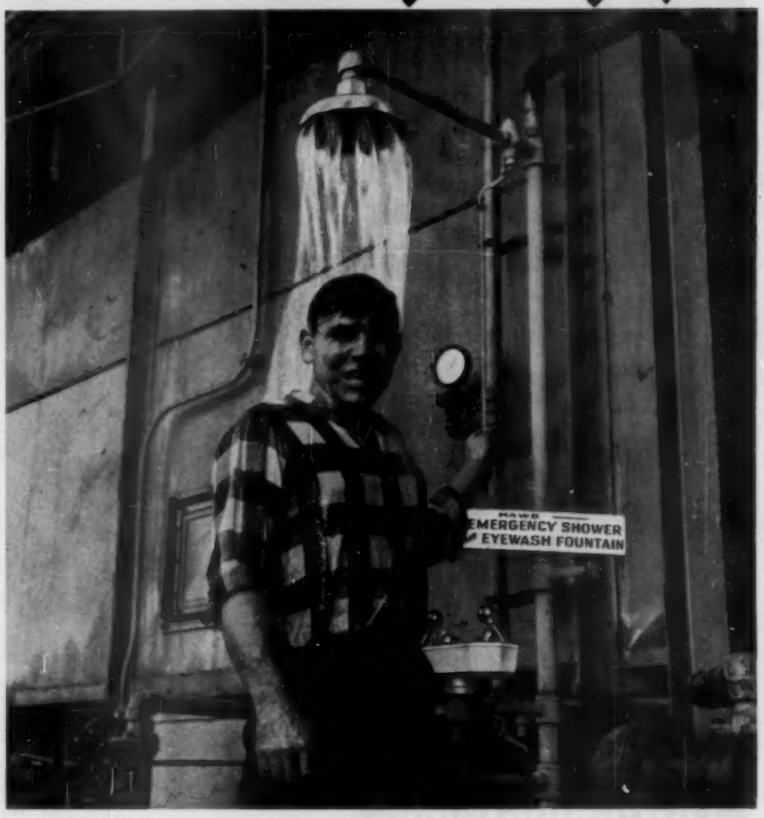

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For further technical information or engineering aid, write Tobe Deutschmann Corporation, Norwood, Mass.

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ously variable from 500 to 1,500 v); linear amplifier (31 channels, gain of 1 or 3.2, channel width of 3% or 1%, zero drift 1 channel per day) and analog-to-digital converter (avg. dead time 50 μsec, max. input pulse rate 50,000 cps, coincidence and anticoincidence, 1.5 μsec resolution); control circuit with analyzer mode (preset timer selection from 0.1 sec to several days in steps of factors of two with 1% accuracy for measurements longer than $\frac{1}{10}$ min) and gross counting mode (preset count selection from 10 to several billion in steps of factors of two); Arithmetic circuits (count up to 100,000,000).—Radiation Counter Laboratories, Inc., 5121 W. Grove St., Skokie, Ill.

Pocket Dosimeter

The PTW "Monitor" is integrating pocket dosimeter that will sound audible alarm as soon as bearer has received radiation dose of 20 mr or 30 mr. It can also be supplied on special orders for any other capacity. It weighs 12½ ounces and measures 4¼ × 2¾ × 1½ in.—George T. Meillon Inc., 132 Nassau St., New York 38, N. Y.

LITERATURE AVAILABLE

Electronic apparatus for science and industry are described in 256-p Catalog O.—General Radio Co., 275 Massachusetts Ave., Cambridge 39, Mass.

"Health Physics Manual" contains table of organization; permissible exposure levels; radiation hazard control methods, apparatus and procedures; application of procedures at each stage of operation of high-level irradiation facility; emergency procedures; training program; and large appendix including glossary, chemical and nuclear data, sample forms, etc.—Inland Testing Laboratories Div., Cook Electric Co., Morton Grove, Ill.

Teflon hose and reusable fittings are subjects of 4-p catalog supplement.—Titeflex, Inc., Hendee St., Springfield 4, Mass.

Data logger and alarm scanner featuring "building-block" construction and flexible pinboard programming is described in 6-p Catalog 30A1200.—Fischer & Porter Co., 464 Jacksonville Rd., Hatboro, Pa.

Tray-type deaerators for effective removal of corrosive gases from boiler feedwater are discussed in 6-p Bulletin 28B8853.—Allis-Chalmers Manufacturing Co., Milwaukee 1, Wisc.

Measurement and control instrumentation is described in loose-leaf bulletin.—Schaevitz Engineering, P. O. Box 505, Camden 1, N. J.

Detecting, counting and analyzing systems are contained in 132-p Catalog 17, covering complete line of 200 items, with special section on applications.—Radiation Counter Laboratories, Inc., 5121 W. Grove St., Skokie, Ill.

"New and Recent Devices" is title of 8-p publication on chemistry and biology laboratory equipment.—Aloe Scientific Div., A. S. Aloe Co., 5655 Kingsbury, St. Louis 12, Mo.

"Zirconium and Zircaloy" is title of 2-p Bulletin IND-16.—General Plate Div., Metals & Controls Corp., Attleboro, Mass.

Radiation detection instruments are described in 24-p Catalog B7-56.—Nuclear Measurements Corp., 2460 N. Arlington Ave., Indianapolis 18, Ind.

Electrothermal heaters for use on metal or glass vessels and pipe are described in three pamphlets.—Arthur S. LaPine & Co., 6001 S. Knox Ave., Chicago 29, Ill.

Radioisotope equipment for medical purposes is subject of 32-p booklet.—Tracerlab, Inc., 1601 Trapelo Rd., Waltham 54, Mass.

Amplifiers for use in radiation monitoring, scintillation spectroscopy and proportional-counter analysis are covered in 4-p bulletin.—Hamner Electronics Co., P. O. Box 531, Princeton, N. J.

Deuterium-labeled compounds are given in current-price list.—Volk Radiochemical Co., 5412 N. Clark St., Chicago 40, Ill.

"Zircoa News" is title of 4-p newsletter covering latest developments in use of zirconia. Sample subject: zirconia as catalyst and catalyst support.—Zirconium Corp. of America, Solon, Ohio

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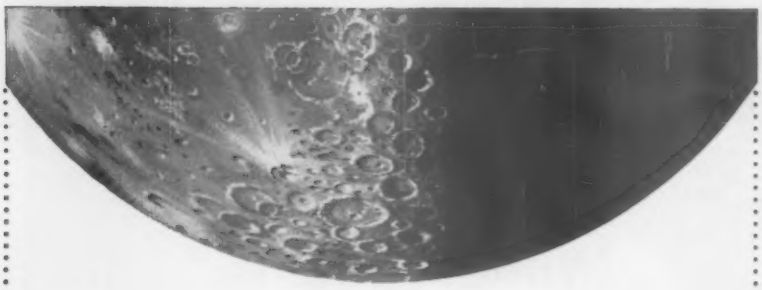

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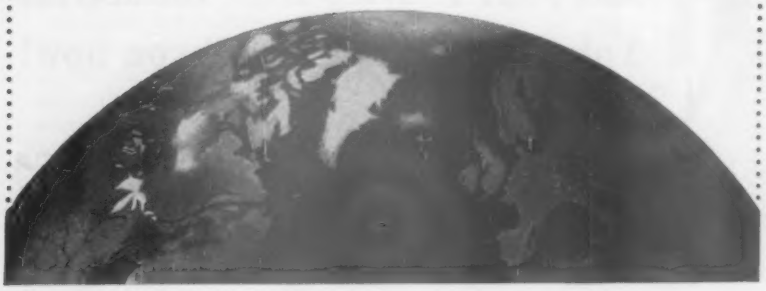

PRODUCTS & MATERIALS

Department starts on page 130

the story of Mallinckrodt's part in nuclear fuel production.—Mallinckrodt Chemical Works, 2nd & Mallinckrodt Sts., St. Louis 7, Mo.

Industrial ceramics and custom services, including production, prototype design, research and development, are described in 6-p bulletin.—Thermo Materials, Inc., 4040 Campbell Ave., Menlo Park, Calif.

Radiological health and safety consulting service to handlers and users of radioactive materials who do not have facilities or trained personnel to adequately monitor their operations is described in 8-p pamphlet.—Combustion Engineering, Inc., 200 Madison Ave., New York 16, N. Y.

CON-RAD has available a 6-p pamphlet summarizing its applied nuclear research and radioanalytical services and an 8-p brochure describing its radiation-protection program.—Controls for Radiation, Inc., 130 Alewife Brook Pkwy, Cambridge 40, Mass.

Controls for valves, drives, pumps, tools, etc., both shaft-mounted positioning gearmotor and digital systems, are presented in 8-p Bulletin J-101.—The Jordan Co., Inc., 3235 W. Hampton Ave., Milwaukee 9, Wisc.

Electrochemical technical data is presented in 16-p Booklet 2152. Among materials covered are various borides, boron carbide, zirconium oxide and boron.—Norton Co., Worcester 6, Mass.

Coextrusion is subject of 6-p Bulletin 10 discussing recently developed techniques that have enabled the fabrication of many combinations of metals in the form of tubing, rods and special shapes.—Nuclear Metals, Inc., 224 Albany St., Cambridge 39, Mass.

Periodic table of the elements in color is available through permission of W. M. Welch Manufacturing Co., copyright owner.—Atomic Development Mutual Fund, Inc., 1033 30th St., N. W., Washington 7, D. C.

Springs for high-temperature use, is subject of 8-p reprint that tells how to design and select materials and why.—Associated Spring Corp., Bristol, Conn.

High-torque actuator motor featuring split-second starting and stopping with starting torque equal to running torque is described in 1-p engineering bulletin. —Viking Tool & Machine Corp., 20 Main St., Belleville 9, N. J.

Filters and strainers for fluids and gases is subject of Catalog 58-100.—The Cuno Engineering Corp., S. Vine St., Meriden, Conn.

Electrical controls, simple and for all purposes, are described in 12-p Bulletin 106.—Assembly Products, Inc., 75 Wilson Mills Rd., Chesterland, Ohio.

Millisecond operations recorder for continuous automatic logging of power-station operations is described in Catalog 30A1400.—Fischer & Porter Co., 488 Jacksonville Rd., Hatboro, Pa.

Servo analysis worksheets have been prepared to help engineers working on system, or component, test and design. —Servo Corp. of America, 20-18 Jericho Tnpk, New Hyde Park, N. Y.

Solenoid valves featuring plunger-seal design are described in Catalog 105.—Dept. 717, Valcor Engineering Corp., Carnegie Ave., Kenilworth, N. J.

Helium, with its physical and thermodynamic properties, is subject of plastic-bound book containing tables, diagrams, gas curves and little-known facts.—Wm. R. Whittaker Co., Ltd., 915 N. Citrus Ave., Los Angeles 38, Calif.

INDUSTRY NOTES

Cook Electric Co., Chicago, Ill., has a Health Physics Department to advise companies wishing to establish radiation safety programs, conduct radiological safety training and education programs, or assist an established organization in solving its operational problems.

Gerard G. Leeds Co. of Great Neck, N. Y., manufacturer's representatives, operate a mobile demonstrator that can bring complete lab setups, including multichannel analyzers, air monitors and area-monitor installations, for field demonstration and test. The company presently represents **Radiation Instrument Development Laboratory,** Chicago, Ill., (multichannel analyzers, scalers, etc.); **Eberline In-**

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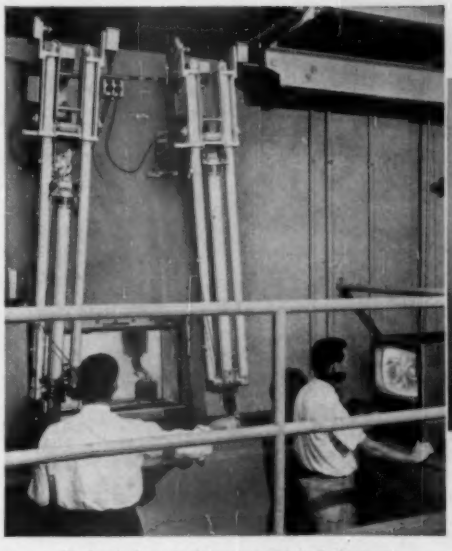

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strument Division of Reynolds Electrical & Engineering Co., Santa Fe, N. M. (health physics monitoring and survey instruments); **Narda Ultrasonic Corp.**, Mineola, N. Y. (ultrasonic cleaning equipment) and **St. John X-Ray Laboratory**, Califon, N. J. (film-badge service).

Central Electronic Manufacturers, Inc., Denville, N. J., a subsidiary of **Nuclear Corp. of America, Inc.** is adding some 11,000 sq ft of floor space to be used, among other things, to provide more room for its nuclear research and development operation.

Minneapolis-Honeywell Regulator Co. will supply the instrumentation for the plutonium extraction plant at Marcoule, France. Automatic control of the three-reactor plant (G-1, G-2, and G-3 are expected to turn out more than 200 lb of Pu annually) will require about 485 indicators on 11 panels. Also to be equipped with Honeywell automatic controls are the research reactors being built by **AMF Atomics** at Munich, West Germany and **ACF Industries, Inc.** at Ispra (Varese), Italy.

Broadview Research Corp., which has been active in the areas of computer application and marketing, physics, chemistry and engineering research, has opened a new data-processing center in San Francisco, Calif. that includes an ALWAC III-E digital computer. Other offices of Broadview are in Washington, D. C., Burlingame, Calif. and Sierra Vista, Ariz.

American Potash & Chemical Corp., Los Angeles, Calif., has begun production of a series of rubidium and cesium compounds, including the carbonate, sulphate, chloride and fluoride.

Pilot Chemicals, Inc., has moved its plant and offices from Waltham to Watertown, Mass. In its improved and expanded facilities, the company will increase production of its line of high-purity fluors and plastic scintillators.

BJ Electronics, division of Borg-Warner Corp., Santa Ana, Calif., has appointed J. W. Woodruff to the newly created post of manager, customer relations, to coordinate and follow through customer purchases and contracts.

NUCLEAR CAMPUS

• **Fifth Series of AEC Grants.** AEC, scheduling its fifth series of grants to colleges and universities for the purchase of laboratory equipment in the teaching of nuclear science and engineering, asked interested schools to file their requests by May 1. Under a separate program in the life sciences, AEC has just completed a second series of grants—$373,559 to 30 schools. Since Oct. 15, 52 schools have collected $713,597.

• **Fellowship Awards.** AEC has awarded two groups of graduate fellowships for the school year beginning this summer—165 fellows in nuclear science and engineering and 89 in radiological physics (the study, evaluation and control of radiation hazards). The radiological program will be carried out at four institutions—Vanderbilt, Rochester, Washington and Kansas. After nine months of academic study, the Vanderbilt fellows will get three months of experience at Oak Ridge National Laboratory; Rochester fellows to Brookhaven; and Washington and Kansas fellows to Hanford Atomic Products, Wash.

• **North Carolina State College** School of Engineering has received an AEC grant of $106,779 to permit the school to acquire nuclear training equipment for the departments of civil, chemical and mechanical engineering, according to J. Harold Lampe, dean of engineering. Studies to be supported by the grant include heat transfer in nuclear power plants, radioactive waste disposal, thermal problems and separation processes.

• **Stanford University** has established a nuclear technology laboratory headed by George Leppert. Equipment includes a subcritical assembly, a counter room for measuring and analyzing radioactivity, a heat-transfer research lab and a machine shop. Planned for next year is a radiochemistry lab for training in the use of radioisotopes.

Stanford's subcritical assembly was designed and assembled by a graduate student, Eugene T. Jilg, under Leppert's supervision.

• **High Voltage Engineering Corp.** has unveiled a new Van de Graaff particle accelerator designed especially for pulsed neutron output in conjunction with subcritical assemblies, reactor de-

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MODELS	403M	402M	400CEM	404M	405	400BDA
OUTPUT VOLTAGE	500 to 1600 volts	500 to 1600 volts	500 to 1600 volts	500 to 2000 volts DC	600 to 3100 volts DC	500 to 5100 volts DC
OUTPUT CURRENT	0 to 1 ma	0 to 1 ma	0 to 1 ma	0 to 5 ma at 500 to 1500 volts; 0 to 2 ma at 1500 to 2000 volts	0 to 15 ma DC	0 to 1 ma
OUTPUT POLARITY	pos. or neg.	pos. or neg.	pos. or neg.	pos. or neg.	pos. or neg.	pos. or neg.
REGULATION VS. LINE	.03% max. from 100 to 130 volts	.03% max. from 100 to 130 volts	.01% max. from 100 to 130 volts	.01% max. from 100 to 130 volts	.01% max. for 20% line change	.01% max. from 100 to 130 volts
REGULATION VS. LOAD	.03% no load to full load	.03% no load to full load	.01% max. for 2 ma change	.01% max. for 2 ma change	.005% for 10 ma change	.01% max. no load to full load
STABILITY	.02% per hour	.01% per hour	.005% per hour	.005% per hour	.005% per hour	.005% per hour
RESOLUTION	100 mv at any output voltage	100 mv at any output voltage	100 mv at any output voltage	100 mv at any output voltage	10 mv at any output voltage	100 mv at any output voltage
CALIBRATION ACCURACY	2%	1%	Better than 1%	Better than 1%	Better than .5%	1%
RIPPLE	5 mv max.	5 mv max.	Less than 5 mv RMS	Less than 5 mv RMS	Less than 5 mv RMS	5 mv max.
SIZE AND WEIGHT	19"W x 7"H x 13"D—22 lbs.	19"W x 7"H x 13"D—22 lbs.	19"W Rack x 7"H x 13"D	19"W Rack x 7"H x 13"D—27 lbs.	19"W x 10½"H x 14"D—46 lbs.	19"W x 10½"H x 14"D—43 lbs.
PRICE	$209.00	$265.00	$395.00	$435.00	$505.00	$595.00

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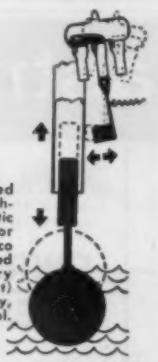

A sleeve, raised and lowered within a nonmagnetic tube, attracts or releases an Alnico magnet attached to the mercury (or dry contact) switch. Basically, this is Magnetrol.

The operating principle behind MAGNETROL LIQUID LEVEL CONTROL

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NUCLEAR CAMPUS

Department starts on page 143

sign studies and nuclear engineering training. The positive-ion machine, Model PN-250, has an energy rating of 0.25 Mev, nominal, with nominal ion current during pulse of 50 μa. Weight is 1,200 lb.

• **Georgia, South Carolina and Tennessee** are sending 13 specially trained "traveling teachers" on lecture-demonstration tours during the 1958–59 school year. The teachers will spend a three-month preliminary training period at Oak Ridge Institute of Nuclear Studies under the Traveling Science Demonstration Lecture Program, sponsored by AEC and the National Science Foundation. Another nine teachers are expected to be enrolled before the preliminary course begins this summer.

• **Brooklyn College and University of Detroit** have received access permits from AEC under the program for making restricted data of use in the peaceful application of atomic energy available to parties with a demonstrated need for the data.

Courses

Massachusetts Institute of Technology will offer a special summer program in **principles of radioisotope utilization** from July 14 through July 25. Topics to be covered include atomic and nuclear physics, dosimetry, radiochemistry, detection of radiation, radiation effects, and theory of tracer experiments. Afternoon sessions emphasize industrial and medical applications of radioisotopes. Tuition is $250; academic credit is not offered.

A lecture series on **materials for nuclear reactors** will be held at New York Univ. June 9–13. The schedule includes 20 lectures, with a different aspect of reactor technology to be covered on each of the five days—criteria for materials selection; properties of materials; environmental (including radiation) effects; fuel materials and systems; design problems.

The Maritime Administration is continuing its courses in **atomic, biological, chemical and damage control training** through June. Application to attend the two-day course given biweekly should be made at Rm. 822, 45 Broadway, New York City.

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NEWSMAKERS

AEC has completed a top-level realignment of its legal staff, naming **Algie A. Wells** deputy general counsel to **Loren K. Olson**, general counsel, and **Edward Diamond**, associate general counsel. Olson and Diamond were appointed earlier this year. Wells has been a member of the legal staff since 1949.

Herbert F. York has left his post as director of the Univ. of California Radiation Laboratory, Livermore, to head the Division of Advanced Research Projects at the Pentagon. He has been succeeded by **Edward Teller**, an important contributor to development of the hydrogen bomb. Teller will retain his positions as professor of physics at the university and associate director of the Berkeley section of the laboratory. York, only 37, has had a meteoric rise since he entered the atomic energy program in 1943. An expert on atomic weapons, he serves on advisory committees to the air force, army, secretary of defense and President Eisenhower.

York

Teller

Two staff members of the Joint Committee on Atomic Energy have been given promotions: **John T. Conway** as assistant director to **James T. Ramey**, and **David R. Toll** as staff counsel, succeeding **George Norris, Jr.** Norris recently joined Combustion Engineering. The other professional staff members of JCAE are **Edwin Brown, Jr.** and **Captain N. R. Nelson, USN.**

Canada's atomic energy director, **William J. Bennett**, has resigned to enter private business. He headed the atomic program for nearly five years.

The Martin Company has made three personnel changes in its Martin-Nuclear div. **John C. Robinson**, former manager of Sylvania-Corning's fuel element plant, is new manager of Martin-Nuclear's engineering dept.; **Jack Hunter** has gone from engineering manager

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Dual-Purpose Reactors

This article starts on p. 105

all costs now borne by the existing Hanford reactors). For the power-producing reactors, the power was credited against Pu cost at a rate of $25/kw-yr(3.58 mills/kwh at 80% load factor). This value was recommended by the Federal Power Commission and appears a reasonable one for the Columbia River basin area where the plant would be integrated into a large hydroelectric network.

The estimates also take into account the possibility that the demand for Pu may not continue for the useful life of the plant. Thus two situations were assumed: (a) Pu demand lasts for only the first ten years of plant life. The single-purpose reactor is then written off at the end of this period while the dual-purpose reactors produce saleable power for 15 more years. (b) Pu demand continues and all reactors remain in operation for 25 years.

Under the latter assumption the full-cost figures show that the single-purpose and the 300-Mw reactor costs are about the same. The 700-Mw reactor produces Pu at a 30% lower cost (although at a lower rate). For 10-year Pu production the single-purpose and the 300-Mw reactor again come off about equal while the 700-Mw design is still lower by some 30%. The conclusion to be drawn is that for a significant reduction in Pu costs (compared with single-purpose reactor costs), dual-purpose units of the size considered must produce more than 300 Mw of electric power.

Brief studies of Pu cost under government financing at another site showed a comparable cost assuming the power is sold at 3.58 mills/kwh and was 20% lower for a value of 6.5 mills/kwh. The use of the former value for Hanford depends on the region's hydroelectric network being able to accept large fluctuations in reactor power output (from sudden outages or scheduled shutdowns). The report expressed doubt that other networks in the country could afford to pay even the lower price for this kind of power. Estimates of the cost of Pu under private financing at either the Hanford site or another site showed the product cost doubled or quadrupled over the government cost.

The report suggested that a four year period would be needed to build any of the reactors starting from date of authorization.

Gas-Cooled Reactors

This article starts on p. 104

The specific power (Mw/ton of fuel) of the natural-uranium is only one third the specific power of an enriched system of comparable output. This is reflected in large reactor vessel, more fuel channels and a generally larger plant. Capital costs per unit capacity for large-scale natural-uranium plants are ~30% higher than for comparable plants using partially enriched U.

At a burnup of 2,700 Mwd/ton, fuel costs for natural uranium come out to be about the same as for partially enriched fuel at 9,000 Mwd/ton. In both instances the fuel cost is about 2.5 mills/kwh including fabrication, burnup, processing, and 4% charges on uranium inventory with a credit for plutonium at $12/gram. Kaiser estimates that the power cost for a natural-uranium reactor equivalent to the 215-Mw(e) plant mentioned above would be 16.2 mills/kwh.

Also natural-uranium concepts show relatively poor development potential. There is little evidence that any major improvements can be made in the technology of natural-uranium gas-cooled, graphite-moderated power reactors. (See p. 102 for British views.)

AEC Recommendations

The AEC made these recommendations for a future gas-cooled graphite-reactor program if the U. S. should decide to follow one:

- Rather than start out with a large scale [~200 Mw(e)] gas-cooled reactor as a prototype, AEC believes a smaller one [~40Mw(e)] would be easier to build, cost less money and give all the information needed. The reactor should be designed for exit gas temperatures of at least 1,000° F and for steam conditions approaching those of modern plants.
- This or any other gas-cooled graphite concept should definitely use enriched rather than natural uranium.

However, some attention should be given to the long range potential of natural-uranium feed with Pu-recycling, applying technology derived from other phases of the development program.

- Any program adopted should include design studies on more advanced large-scale gas-cooled power-reactor concepts and a comprehensive research effort on gas cooling, high-temperature graphite characteristics, and high-temperature fuel materials.

NEWSMAKERS

Department starts on page 145

to technical director; and **V. Keith Young** has moved from facilities administrator to assistant general manager.

Harry L. Hilyard, vice-president–treasurer of American Tobacco Co., has been elected president of Industrial Reactor Laboratories, Inc., succeeding **Walter Bedell Smith,** vice chairman of American Machine & Foundry. **E. J. Goett,** senior vice-president of Atlas Powder, has been elected vice-president of IRL; **W. I. Chamberlain,** AMF, has been re-elected secretary; and **J. S. Hanks,** IRL business manager, has been re-elected treasurer.

Hilyard

Otto A. Schulze has been appointed engineering manager, AMF Atomics. He formerly headed a section of the parent firm's nuclear engineering laboratory, now a part of AMF Atomics.

General James M. Gavin, retired chief of research and development, U. S. Army, has been elected vice-president of Arthur D. Little.

Everett R. Holles, personal assistant to AEC chairman **Lewis L. Strauss,** has joined General Atomic div., General Dynamics, as assistant to **Frederic de Hoffmann,** vice-president of GD and general manager of GA. Holles served with Strauss for more than three years, participating in the preparations for the Geneva Conference in 1955 and advising the U. S. delegation to the International Atomic Energy Agency conference in Vienna last year.

Holles

L. Stewart Mims has joined Atomics International as group leader of preliminary engineering. Mims is former director of Bell Aircraft's nucleonics dept. and, before that, manager of the analytical design section, Westinghouse Bettis div.

Montgomery H. Johnson has taken on responsibility for all basic scientific research operations of Aeronutronic Systems, Inc., subsidiary of Ford Motor Co. He was director of the nucleonics and physics laboratory.

AEC has elevated **Enzi DeRenzis,** assistant deputy manager of the New York Operations office, to manager of the new area office at Princeton, N. J. The office was organized April 1 to supervise the controlled thermonuclear and other high-energy physics research work at Princeton Univ.

Six new employees have been hired by the Atomic Energy div., Phillips Petroleum. They are physicists **Robert Engle, Lester Stephen** and **Rufus Walker;** reactor engineer **Stephen W. Gleave;** electronics engineer **Richard I. Little;** and radiochemist **Robert L. Tromp.**

A. Stanley Thompson has taken over management of engineering operations at Nuclear Development Corp. of America. He will direct the extensive engineering required to take reactor designs from the computing machine to the hardware stage. He joined NDA from General Atomic div., General Dynamics.

Two U. S. scientists have taken leaves of absence to work with the International Atomic Energy Agency. **John H. Manley,** Los Alamos, has been appointed senior technical advisor to the U. S. mission for six months; **W. W. Grigorieff,** Oak Ridge Institute of Nuclear Studies, has been named chief of the exchange branch of the IAEA div. of exchange and training of scientists and experts for a year.

S. C. Sigoloff and **H. M. Borella** have joined Edgerton, Germeshausen and Grier, Las Vegas, upon leaving Nuclear Corp. of America, where they worked on high-level radiation dosimetry and health physics.

Bendix Aviation has assigned **Albert B. Van Rennes** to head its nuclear technology group and **Jack M. LaRue** to a staff advisory post on extension of the firm's activities in reactor design. LaRue formerly headed the technology group.

Jacob Bigeleisen, senior chemist at Brookhaven National Laboratory, has been awarded the $1,000 American Chemical Society award for nuclear applications in chemistry.

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NUCLEAR CALENDAR

May 24–31—International Water Supply Assn., 4th Congress, Brussels. Lecture on atomic energy and its relation to water supply. Contact L. Millis, International Water Supply Assn., 10 Square Ambiorix, Brussels 4.

May 27–29—Third annual reactive metals conference, American Institute of Mining, Metallurgical and Petroleum Engineers, Buffalo (*Statler*). Contact S. F. Urban, National Lead Co., Buffalo, N.Y.

June 1–6—1958 Industrial Research Conference, Harriman, N. Y. (*Arden House*). Speakers include A. P. Hewlett, vice president of Esso Research & Engineering, and John C. R. Kelly, Jr., manager of technology dept., Westinghouse. Fee $400. Contact Robert T. Livingston, 409 Engineering, Columbia Univ., New York 27.

June 2–5—American Nuclear Society annual meeting, Los Angeles (*Statler*). Contact W. R. Hainsworth, Fluor Corp., Los Angeles.

June 2–6—Symposium on the Peaceful Uses of Atomic Energy in Australia, Sydney. Exhibition and five-section conference—materials, power engineering, power auxiliaries (fuel cycles, chemical processing, economics), basic sciences (nuclear and thermonuclear), and associated techniques (radioisotopes, handling instrumentation, health, education, training). Contact Symposium General Secretary, AAEC Research Establishment, Sutherland, New South Wales, Australia.

June 2–7—International Conference on Solid State Physics in Electronics and Telecommunications, Brussels. Scheduled in conjunction with Brussels Fair. Papers on radiation-sensitive materials, phosphors, electroluminescent materials, infrared detectors, image amplifiers, light amplifiers, etc. Contact General Secretary, Société Belge de Physique, Loverval, Belgium.

June 9–11—Annual meeting of Health Physics Society (*University of California, Berkeley*). Contact Elda E. Anderson, Oak Ridge National Laboratory, Tenn.

June 9–12—Conference on Materials Handling, Cleveland (*Public Auditorium*), sponsored by American Society of Mechanical Engineers. Paper June 11 on "development of nuclear handling equipment"; also session June 12 on "materials handling in the atomic and space age." Contact Clapp & Poliak, Inc., 341 Madison Ave., New York 17.

June 15–19—Semiannual Meeting of The American Society of Mechanical En-

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gineers, Detroit (*Statler*). Program includes session on nuclear power program and tour of Enrico Fermi fast breeder reactor under construction at Lagoona Beach, Mich. Contact ASME, 29 West 39th St., New York 18, N. Y.

June 16–20—Fifth Annual Meeting, International Congress on Electronics and Atomic Energy, Rome. Concurrent exhibition on peaceful uses of atom will run through June 30.

June 19–21—5th annual meeting, Society of Nuclear Medicine, Los Angeles. Seminar on teaching problems in use of radioactive isotopes features program which includes 30 scientific papers and four training courses. Contact G. C. Kyker, ORINS Medical Div., Box 117, Oak Ridge, Tenn.

June 23–27—1958 Gordon Research Conference on Nuclear Chemistry, Meriden, N. H. (*Kimball Union Academy*). Talks on nuclear spectroscopy, photonuclear reactions, heavy ion reactions, hot atom chemistry, chemical techniques. Contact W. George Parks, U. of Rhode Island, Kingston.

June 24—Third Annual Symposium on Radiation Effects, Boston (*Statler*), sponsored by American Society for Testing Materials and Atomic Industrial Forum. Papers on dosimetry, new irradiation facilities, and irradiation studies on organics, metals and ceramics. Contact J. H. Kittel, Argonne National Laboratory, Lemont, Ill., or A. N. Tschaeche, Sandia Corp., Albuquerque.

June 30–July 5—2nd Conference on High Energy Nuclear Physics, European Council for Nuclear Research, Geneva. 8th in series of annual conferences hitherto held in Rochester, N. Y. Contact CERN, Geneva 23, Switzerland.

July 7–12—International Congress on Nuclear Physics, Paris, sponsored by the International Union of Physics and the United Nations Economic and Social Council. Contact F. Netter, Institut du Radium, 11, rue Pierre Curie, Paris 5.

Sept. 1–13—Second International Conference on Peaceful Uses of Atomic Energy, Geneva, sponsored by United Nations. For preliminary program, see NU, Aug. '57, 23. As in 1955, there will also be both government-sponsored and industrial exhibits. Contact Sigvard Eklund, United Nations, N. Y.

Oct. 15–17—Second Energy Resources Conference, Denver (*Brown Palace*). General theme is "energy and its impact on society"; also discussion of the world's oceans as an energy source. Speakers include Warren Johnson, Univ. of Chicago, reporting on the Geneva conference. Contact Denver Chamber of Commerce.

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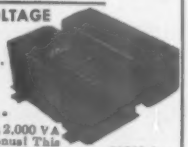

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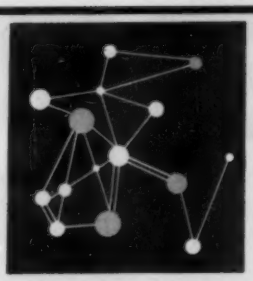

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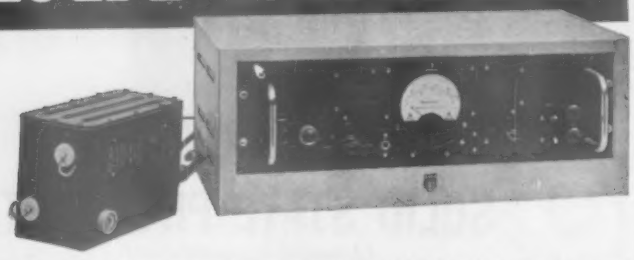

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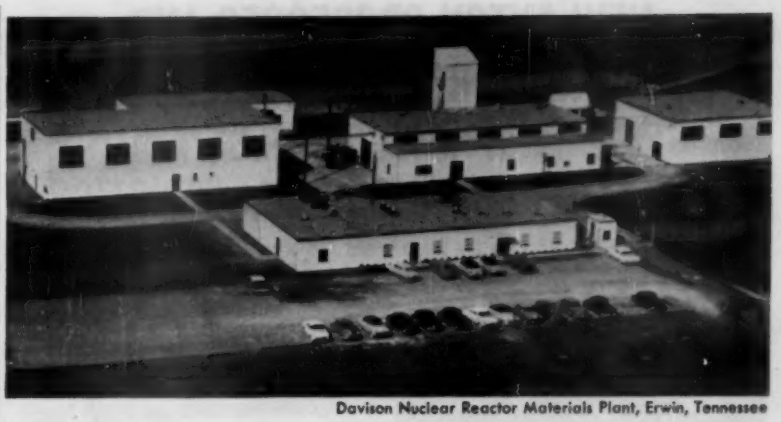

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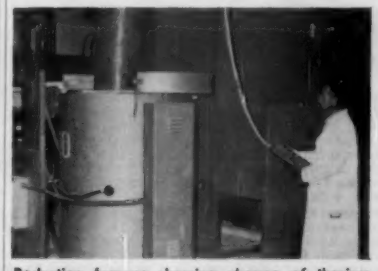

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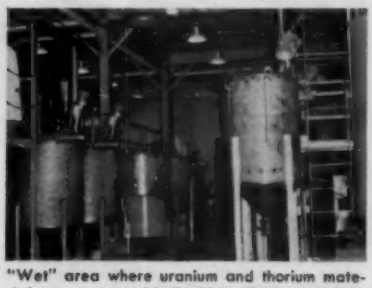

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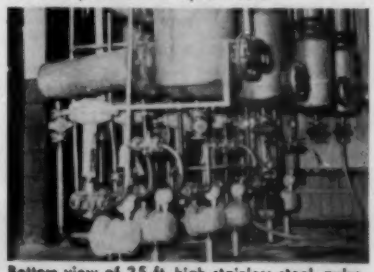

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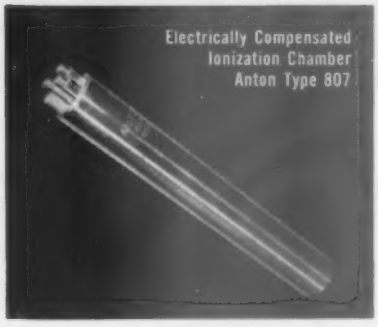

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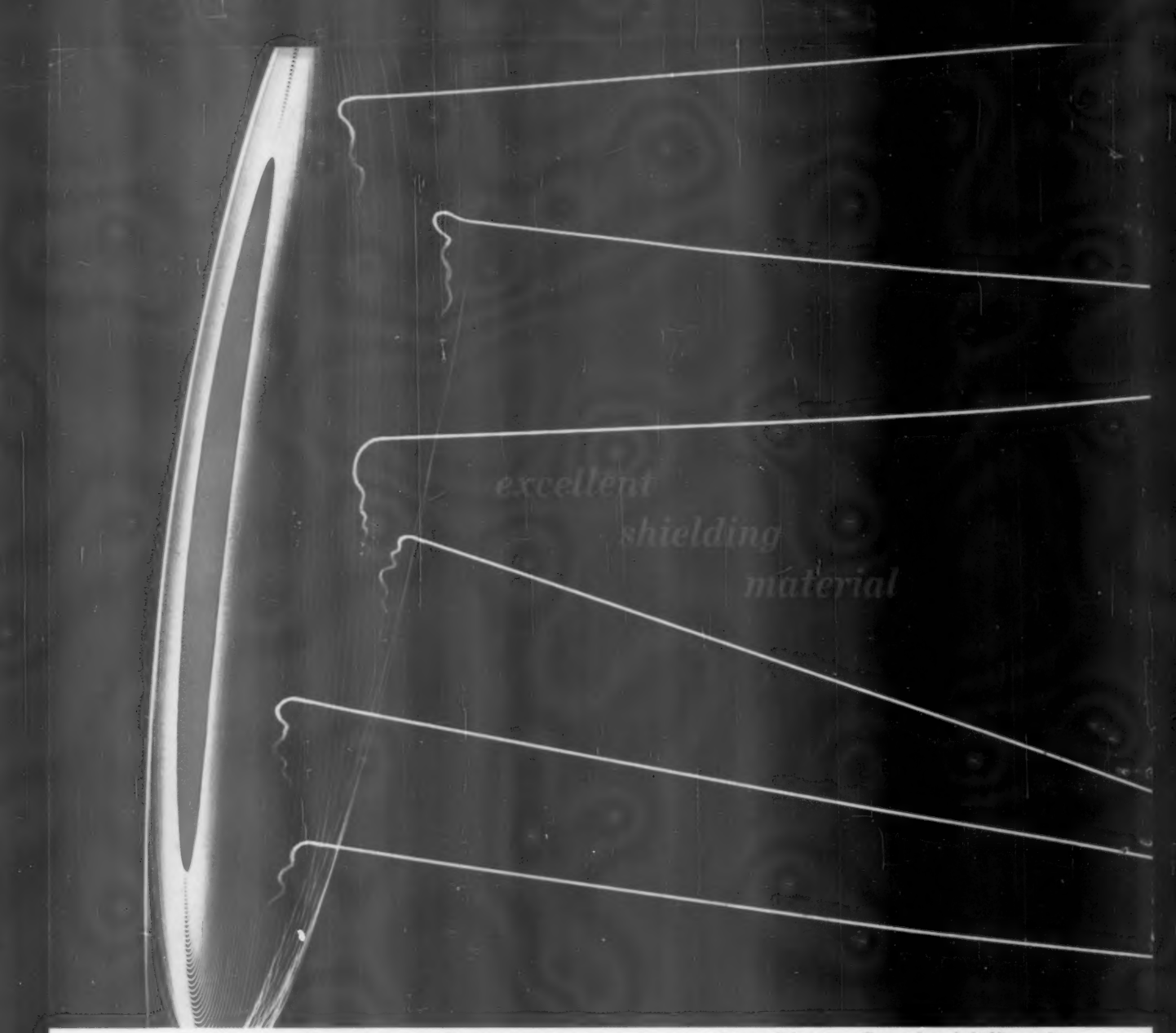

Dynamic light patterns illustrate boron's shielding qualities.

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